CERE Working Paper, 2012:16

Pollution Generating Technologies and Environmental Efficiency

Rolf Färe[a,b] Shawna Grosskopf[a,c], Tommy Lundgren[c], Per-Olov Marklund[c,d], and Wenchao Zhou[d]

[a]Dept. of Economics, Oregon State University, Corvallis, OR, USA
[b]Dept. of Applied Economics, Oregon State University, Corvallis, OR, USA
[c]CERE, Centre for Environmental and Resource Economics, Dept. of Economics, Umeå University, Sweden
[d]CERUM, Centre for Regional Science, Umeå University, Sweden

The **Centre for Environmental and Resource Economics** (CERE) is an inter-disciplinary and inter-university research centre at the Umeå Campus: Umeå University and the Swedish University of Agricultural Sciences. The main objectives with the Centre are to tie together research groups at the different departments and universities; provide seminars and workshops within the field of environmental & resource economics and management; and constitute a platform for a creative and strong research environment within the field.

Department of Economics, Umeå University, S-901 87, Umeå, Sweden

www.cere.se

Pollution Generating Technologies and Environmental Efficiency[1]

Rolf Färe[a,b] Shawna Grosskopf[a,c], Tommy Lundgren[c], Per-Olov Marklund[c,d], and Wenchao Zhou[d]

[a]Dept. of Economics, Oregon State University, Corvallis, OR, USA
[b]Dept. of Applied Economics, Oregon State University, Corvallis, OR, USA
[c]CERE, Dept. of Economics, Umeå University, Sweden
[d]CERUM, Umeå University, Sweden

Abstract

In this paper we study environmental efficiency within a pollution generating technology. Pollutants, or bads, are explicitly modeled by imposing technology properties of disposability and null-jointness. With data on firms from Swedish manufacturing, we investigate the potential to reduce emissions, and we take a closer look at the pulp and paper sector. Dividing the firms into "brown" and "green" firms, we find that there is significant potential, in both categories, to improve environmental efficiency, and hence lower emissions, of three air pollutants. Furthermore, we suggest that treating biofuels as entirely carbon neutral (as is common practice) may underestimate environmental efficiency scores and generate misleading policy implications.

[1]Corresponding author: Zhou Wenchao, wenchao.zhou@cerum.umu.se .

1 Introduction

The impact of firms' activities on the environment receives increasing attention from environmentalist and policy makers, and growing awareness of the environmental damages calls for immediate and effective actions. In this context, contributions from research integrating the scientific fields of environmental economics and productive efficiency are most crucial, providing policy makers and firms managers with knowledge to improve environmental policy design and environmental behavior. In this paper we focus particularly on modeling firms' activities with pollution generating technologies to provide further insight into firms' environmental efficiency.

The goal in this paper is to explicitly study firms' environmental efficiency within the Swedish manufacturing industry, with special focus on pulp and paper. We apply a Data Envelopment Analysis (DEA) model as a pollution generating technology, where bad outputs are by-products produced simultaneously with marketable good outputs. To introduce the opportunity cost of reducing bad outputs, we impose specific technology properties of disposability and null-jointness as proposed by Färe et al. (1986).

As emphasized in Färe et al. (2012), it is most important to account for emissions when evaluating firm performance. Broadly speaking, among studies that impose the technological property of good and bad outputs being together weakly disposable, mainly two strands of studies can be found; those that could be referred to as measuring economic performance and those that could be referred to as measuring environmental performance. The former case includes, e.g., studies on total factor productivity (TFP) that adopt a Malmquist and/or Luenberger productivity index/indicator approach, e.g., Färe et al. (2012), Yu et al. (2008), Kumar (2006), Yöruk and Zaim (2005), Jeon and Sickles (2004), Färe et al. (2001) Weber and Domazlicky (2001), and Chung et al. (1997). All these studies measure productivity change between two years conditional on crediting simultaneous expansion of good outputs and contraction of bad outputs.

Firm behavior may also be measured in terms of environmental performance, but is less common in economics research. A few examples of such studies include Lundgren and Marklund (2012), Brännlund et al. (2011), Färe et al. (2010), Färe et al. (2006), and Färe et al. (2004). They apply an environmental performance index based on Malmquist (1953) quantity indexes, in turn based as ratios of Shephard-type output distance functions. It works as an environmental productivity index that measures essentially the changed amount of good outputs to unit of bad outputs. However, in this paper we suggest a third approach to evaluating firm behavior, i.e., environmental efficiency (EE).

We measure EE as firms' potential to reduce production of bad outputs, while maintaining levels of input resources and good outputs. A few examples of similar earlier studies are Tyteca (1997), and Picazo-Tadeo and Garcia-Reche (2007); both using nonparametric DEA techniques to calculate environmental performance of firms. Tyteca (1997) studies environmental performance in U.S. electric utilities using two different data sets, one for the year 1991 and another for the two years 1987 and 1991, while Picazo-Tadeo and Garcia-Reche (2007) study environmental performance among ceramic-tile firms in Spain 1995. Compared to these studies, the contribution of this paper to the current strand of literature is made possible due to a unique firm level data set, covering all sectors of Swedish manufacturing during 2000 to 2008. From a policy point of view this is relevant as identifying sectors, but also specific types of firms within sectors, with relatively large potential to reducing emissions brings important information to the bigger picture of welfare-enhancing environmental policy. This paper should be seen as a complement to Färe et al. (2012) as it uses the same data but takes a closer look at EE, as opposed to a more general productivity measure.

The data set available: (1) covers thirteen sectors in Swedish manufacturing at the firm level, which we divide into “dirty” (brown) and “clean” (green) firms; (2) covers emissions to air, CO_2, SO_2, and NO_X. By studying EE among brown and green firms (definition given below), we recognize the fact that there may be possibilities for improving environmental performance even for firms regarded as being green. In general, the results show that there is considerable variation in environmental efficiency among the pulp and paper firms, but also among sectors within Swedish manufacturing. The results also show there is potential for improving environmental efficiency among firms, even the relatively environmentally friendly, so called green ones.

The paper is structured as follows. In Section 2 we introduce the methodology of modeling the pollution generating technology. Section 3 presents the data and Section 4 the results. Finally, Section 5 provides some conclusions and discussion.

2 Methodology

In this section we introduce our DEA model of a pollution generating technology that includes production of undesirable by-products as bad outputs.[2]

2.1 The pollution generating technology

Assume that the firm produces M desirable, or good, outputs $(y_1,\ldots,y_M)\in\Re_+^M$ and J undesirable, or bad, outputs $(b_1,\ldots,b_J)\in\Re_+^J$, by using N inputs $(x_1,\ldots,x_N)\in\Re_+^N$.[3] Then, the technology set can be expressed as follows:

[2] This is based on Färe et al. (1989), see also Färe and Grosskopf (2004).

$$T = \{(x, y, b) : x \text{ can produce } (y, b)\}, \tag{1}$$

consisting of all feasible vectors (x, y, b). T is assumed to satisfy certain axioms, e.g., being closed with bounded output sets (compact) and inputs being strongly disposable (see, e.g., Färe and Grosskopf, 2003 for further details). In addition, to allow for undesirable outputs in production some further technological properties are introduced. Good outputs and bad outputs are assumed null-joint, i.e., $if\ (x, y, b) \in T,\ b = 0 \Rightarrow y = 0$, which means that good outputs cannot be produced without producing bad outputs.[4] The null-jointness axiom expresses the phrase 'no fire without smoke'.[5] However, given a positive amount of good output, this does not mean that zero emissions cannot occur. In the case of more than one bad output the null-jointness condition is not violated as long as at least one bad output takes a positive value.

To explicitly introduce the opportunity cost of reducing bad outputs, bad and good outputs are assumed being together weakly disposable, i.e., $if\ (x, y, b) \in T,\ and\ 0 \leqq \theta \leqq 1 \Rightarrow (x, \theta y, \theta b) \in T$. In addition, good outputs are assumed strongly disposable, i.e., $if\ (x, y, b) \in T,\ and\ y' \leq y \Rightarrow (x, y', b) \in T$, meaning that good outputs can be reduced without reducing any other output.

To model T in a DEA setting, assuming that there are K observations, (x^k, y^k, b^k) for $k = 1, \ldots, K$, the pollution generating technology becomes:

$$\begin{aligned} T = \{(x, y, b):\ & \sum_{k=1}^{K} z_k y_{km} \geqq y_m, \quad m = 1, \ldots, M \\ & \sum_{k=1}^{K} z_k b_{kj} = b_j, \quad j = 1, \ldots, J \\ & \sum_{k=1}^{K} z_k x_{kn} \leqq x_n, \quad n = 1, \ldots, N \\ & z_k \geqq 0, \quad k = 1, \ldots, K\}, \end{aligned} \tag{2}$$

where the equality sign in the bad output constraint together with the output inequality constraint models outputs as weakly disposable. The intensity variables,

---

[3] Outputs are considered as desirable if a consumer gets higher satisfaction from consuming more, and to be undesirable if more consumption leads to lower satisfaction, i.e., $y' \geqq y, \quad b \leqq b' \quad \Rightarrow \quad (y', b') \gtrsim (y, b)$ (at least as good as).

[4] The axiom of null-jointness originates from Shephard and Färe (1974).

[5] The assumption of null-jointness can be justified by thermodynamics, see Baumgärtner et al. (2001).

z_k, in Equation (2) are assumed non-negative, which imposes constant returns to scale on the technology, i.e., $\lambda T = T, \quad \lambda > 0$. Furthermore, the following conditions on the data are imposed:

$$\sum_{k=1}^{K} y_{km} > 0, \quad m = 1, \ldots, M \tag{i}$$

$$\sum_{m=1}^{M} y_{km} > 0, \quad k = 1, \ldots, K \tag{ii}$$

$$\sum_{k=1}^{K} x_{kn} > 0, \quad n = 1, \ldots, N \tag{iii}$$

$$\sum_{n=1}^{N} x_{kn} > 0, \quad k = 1, \ldots, K \tag{iv}$$

$$\sum_{k=1}^{K} b_{kj} > 0, \quad j = 1, \ldots, J \tag{v}$$

$$\sum_{j=1}^{J} b_{kj} > 0, \quad k = 1, \ldots, K \tag{vi}$$

Conditions (i)-(iv) where introduced by Kemeny, Morgenstern and Thompson (1956) as a generalization of von Neumann (1945) assumptions. They say that the input and output matrices must have at least one nonzero element in each row and column; see Shephard (1970) for further interpretations. In combination with Conditions (i) and (ii), conditions (v) and (vi) indicate that good and bad outputs are null-joint.

To see that T in Equation (2) can be seen as a pollution generating technology, assume that a decision has been made to produce y^* output, using x^* input, then the output and input constraints constrain the intensity variables to $z_k^*, \ k = 1, \ldots, K$. Hence, by the "bad" constraints a bad output vector $b_j^*, \ j = 1, \ldots, J$, is determined.

Here we estimate the pollution vector by taking $\left(x^*, y^*\right)$ equal to observed input and output. A minimized pollution vector is explicitly estimated by solving the following LP problem for bad output *j*:

$$\min b_j = \sum_{k=1}^{K} z_k b_{kj}, \ k = 1, \ldots, K, \ j = 1, \ldots, J \tag{3}$$

subject to

$$\sum_{k=1}^{K} z_k y_{km} \geqq y^*_m, \quad m = 1,\ldots,M \tag{i}$$

$$\sum_{k=1}^{K} z_k x_{kn} \leqq x^*_n, \quad n = 1,\ldots,N \tag{ii}$$

$$z_k \geqq 0. \tag{iii}$$

However, in order to simulate the pollution generating technology for the median firm we can, by replacing objective function (3) with $\max b_j = \sum_{k=1}^{K} z_k b_{kj}$, also obtain the maximum bad output vector. This is illustrated with the following simple example. Assume that $M = N = J = 1$, $K = 2$, $y_{11} = y_{21} = x_{11} = x_{21} = 1$, $b_{11} = 2$, and $b_{21} = 1$, is observed. Then, if $y^* = x^* = 1$, we have

$$z_1 \cdot 1 + z_2 \cdot 1 \geqq 1$$
$$z_1 \cdot 2 + z_2 \cdot 1 = b$$
$$z_1 \cdot 1 + z_2 \cdot 1 \leqq 1$$
$$z_1 \geqq 0, z_2 \geqq 0$$

and

$$1 \leqq b^* \leqq 2,$$

which shows that, given observed amounts of produced good outputs and used inputs, the potential best minimum amount of emission allowed by the technology equals 1. Similarly, the worst case maximum amount of emission equals 2. Ultimately, the observed amount of emissions, b^*, can be compared to the minimum and maximum boundaries of emission levels allowed by the pollution generating technology (see Figure 2 in Section 4.2).

2.2 Computing environmental efficiency

In order to compute environmental efficiency scores, EE, that relates observed bad output b^* to smallest possible emission level, while maintaining input and good output levels, the following LP is solved for observation k':

$$EE = \min \beta \tag{4}$$

Subject to

$$\sum_{k=1}^{K} z_k y_{km} \geqq y^*_m, \quad m = 1,\ldots,M \tag{i}$$

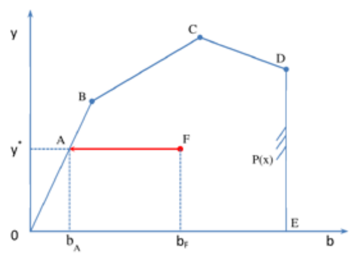
$$\sum_{k=1}^{K} z_k b_{kj} = \beta \cdot b^*_j, \quad j = 1,\ldots,J \tag{ii}$$

$$\sum_{k=1}^{K} z_k x_{kn} \leqq x^*_n, \quad n = 1, \ldots, N \qquad \text{(iii)}$$

$$z_k \geqq 0, \quad k = 1, \ldots, K \qquad \text{(iv)}$$

The constraints in (ii) still guarantee that bad outputs are weakly disposable, but also that observed bad output level is contracted to the smallest possible bad output level. Finally, β takes values between zero and unity, and if $\beta = 1$ firms are environmentally efficient. Figure 1 illustrates the EE indicator, given that the production technology is represented by the output possibilities set, $P(x)$, $P(x) = \{(y,b):(x,y,b) \in T\}$ in Equation (1). This set is piecewise enveloped by observations B to D. The linear section between zero and B is given by good and bad outputs being null-joint and bad outputs being weakly disposable. The section between D and E is given by the good output being freely disposable.

Figure 1. Environmental efficiency as potential of reducing emssions while maintaining levels of input use and production of good output.



Assume that a firm is observed to operate inefficiently at point F. At that point there is a potential to reduce emissions from b_F to b_A, by moving to A. This inefficiency is indicated by $EE < 1$, and emissions could potentially be reduced by $(b_F - b_A)/b_F$ percent. Note that from a pure emission reduction point of view A dominates, e.g., point C, as emissions are lower in A both in absolute and relative terms. Notable also is that from a welfare perspective A is not necessarily preferred to C, as C may better reflect the preferences of society. However, the focus on pure emission reduction potential still brings important information to a bigger picture of welfare enhancing environmental policy.

Another relevant aspect to consider in this context is the firms' cost of becoming more environmentally efficient. At the extremes a firm operating at F may be inefficient compared to a firm operating at A due to differences in polluting generating technologies or, given similar technologies, due to differences in management. Depending on the reason for the difference the cost of moving to A may differ. Is it entirely due to heterogeneity in technologies among profit maximizing firms the cost may be substantial as investment in a greener technology is necessary. However, if the difference is due to managerial problems, allowing for non-profit maximizing behavior, the cost is related to efforts of achieving more efficient use of already available resources.

3 Data

To estimate the pollution generation technology formalized in the previous section, and to analyze environmental efficiency in Swedish manufacturing industry, we use firm level data on 13 different sectors that cover the period 2000 to 2008. The data is the same as used in Färe et al. (2012), especially compiled by Statistics Sweden (www.scb.se), and uniquely detailed and extensive and suitable for studies concerning environmental performance and productive efficiency.

The variables used in estimation are as follows. Firms use four inputs in production, capital stock[6] measured in million SEK, the number of employees, fossil fuels (coal, oil, gasoline) and non-fossil fuels (electricity[7], biofuels, heat), measured in MWh. One good output is produced, which is obtained by dividing firm level sales by a sector level producer price index. Three undesirable by-products are simultaneously produced, carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxide (NO_x), measured in tons. Note that when constructing the CO_2 variable no emissions are coming from biofuels by assumption (carbon neutrality). Therefore, firms that use mostly biofuels in production will seemingly generate very small amounts of CO_2.[8]
Table 1 summarizes the data over the period studied by providing descriptive statistics.

Table 1. Firm level data for the Swedish manufacturing industry, mean values 2000-2008 (base=1990).

	NOBS	Capital (MSEK)	Workers	FossilFuel (MWh)	Non-fossilFuel (MWh)	Output (index)	CO_2 (ton)	SO_2 (ton)	NOx (ton)
Mining	226	567	248	79744	121966	495	24813	28.3	117.8
		(1402)	(582)	(212737)	(332486)	(1073)	(66156)	(86.8)	(406.9)
Food	2101	122	178	10717	10506	392	2564	1.3	2.2
		(189)	(421)	(45481)	(28435)	(841)	(11305)	(9.8)	(11.1)
Textile	601	30	63	3756	3051	65	939	0.6	0.8
		(50)	(69)	(8424)	(8078)	(80)	(2106)	(2.1)	(2)
Wood	1469	60	82	1512	25622	194	407	1.5	4.9

[6] Captial stocks are created from gross investment data using the perpetual inventory method (see Färe et al., 2012 for details).
[7] In Sweden electricity is produced to a large extent using non-fossil intensive methods (hydro and nuclear power, mainly)
[8] Carbon neutrality of biomass fuel is an increasingly debated topic, and for a discussion on what is sometimes referred to as a “climate accounting error, see, e.g., Lundgren and Marklund (2012a, 2012b), Cherubini et al. (2011), and Searchninger et al. (2009).

		(129)	(132)	(5380)	(36448)	(281)	(1488)	(3)	(7.3)
Pulp/paper	808	695	373	71091	364519	965	19034	28.1	46.4
		(1214)	(586)	(142224)	(753410)	(1505)	(38579)	(73.4)	(92.7)
Printing	788	23	64	915	2008	59	222	0.1	0.2
		(29)	(100)	(2280)	(2521)	(139)	(627)	(1.5)	(0.8)
Chemical	962	377	263	26585	50276	600	6605	5.3	6.5
		(1183)	(864)	(73693)	(143130)	(1772)	(18036)	(26.1)	(18)
Rubber/plastic	1152	42	83	2303	5578	106	541	0.1	0.4
		(48)	(95)	(5387)	(7068)	(116)	(1193)	(0.4)	(1)
Stone/mineral	819	67	141	26602	9026	180	7498	6.4	10.6
		(82)	(199)	(66904)	(17393)	(201)	(18515)	(31.6)	(23.2)
Iron/steel	328	526	520	508667	173658	1148	86717	442.4	242.9
		(1036)	(957)	(1794998)	(371131)	(1942)	(294412)	(1790.9)	(899.8)
Metal	1946	10	39	562	1521	29	140	0	0.1
		(11)	(276)	(606)	(3289)	(51)	(153)	(0.1)	(0.2)
Machinery	2871	54	161	1104	4873	258	277	0.1	0.2
		(129)	(359)	(2937)	(13571)	(597)	(704)	(0.5)	(0.6)
Electro	980	71	368	1263	5647	1444	326	0.1	0.3
		(162)	(876)	(1704)	(10575)	(6055)	(446)	(0.5)	(0.4)
Vehicles	967	504	570	6441	19682	1693	1729	2.1	1.7
		(1316)	(1761)	(16899)	(71269)	(4451)	(4983)	(12.5)	(6.2)

Note: standard errors within parenthesis.

The largest emissions are by far occurring in Iron/Steel, followed by Mining and Pulp and paper. It is then pertinent to particularly study environmental efficiency in one of these sectors.

Due to having access to a relatively large number of observations on firms in Pulp and paper, we particularly study environmental performance among 42 brown and 41 green firms in this industry in 2008. Brown firms are defined as having a non-fossil/fossil fuel ratio below the median ratio. Admittedly, this selection rule is ad-hoc, but we still believe it is adequate considering the information we have at hand. Descriptive statistics for brown and green firms are shown in Tables 2a and 2b, respectively.

Table 2a: Descriptive statistics, the Swedish pulp and paper industry data in 2008 (42 brown firms)

Variables	Units	Mean	SD	Minimum	Maximum	Median Firm
Output	MSEK	457.00	772.40	7.60	4677.60	458.47
CO_2	ton	9384.50	18297.30	19.00	110408.00	1137.68
SO_2	ton	8.60	22.90	0.00	141.60	0.02
NO_x	ton	12.90	40.70	0.00	266.20	1.02
Capital	MSEK	234.40	529.00	0.40	3347.20	121.11
Labor	Workers	194.20	239.40	9.00	1036.00	253.00
Fossil fuels	MWh	36315.90	69425.40	74.10	419093.70	5407.28
Non-fossil fuels	MWh	86756.50	231157.30	120.00	1473939.70	11045.00

Table 2b: Descriptive statistics, the Swedish pulp and paper industry data in 2008 (41 green firms)

Variables	Units	Mean	SD	Minimu	Maximum	Median Firm

				m		
Output	MSEK	1616.50	2092.00	24.90	10870.70	1140.00
CO_2	ton	22037.70	35817.60	0.80	168367.50	2056.74
SO_2	ton	39.00	59.40	0.00	275.50	5.18
NO_x	ton	80.20	106.60	0.00	459.50	12.62
Capital	MSEK	1392.80	1778.10	2.70	6811.60	1072.86
Labor	Workers	487.00	632.80	12.00	3490.00	310.00
Fossil fuels	MWh	81210.50	131179.70	3.00	616247.10	7497.60
Non-fossil fuels	MWh	699054.70	1058331.10	410.10	5485764.00	327654.10

Green firms are on average substantially larger than brown firms. One possible explanation is in the differences between different types of firms and how they provide themselves with energy. Firms that produce only pulp, or both pulp and paper, are generally larger than firms only producing paper. Also, the process of producing pulp generates residues that can be used to provide for their own need of energy, i.e., biofuels. Their need for fossil fuels is therefore lower, to a larger extent qualifying them as green firms. It is evident that brown firms use significantly more fossil fuels (as is expected from the brown firm selection rule). The green firms emit more on average because they are much bigger, but the fuel and emission intensity (fossil fuel use or emissions divided by output) is higher for brown firms.

4 Results

4.1 Environmental Efficiency in pulp and paper

In this paper we argue that firms' production technology should be seen as a pollution generating technology, meaning that it is impossible to produce marketable products without causing emissions. Theoretically this is ensured by the null-jointness condition. Furthermore, opportunity costs of reducing emissions are modeled by imposing specific technology properties of disposability.

Empirically we study firms' actually observed emissions compared to their least possible emissions levels given the technology. Focus is especially on green and brown firms in the Swedish paper pulp industry, for the year 2008. Tables 3a and 3b provide results for brown and green firms, respectively, generated by the optimization problems in Equations (3) and (4).

As shown in Table 3a, environmental performance varies considerably among brown pulp and paper firms. For the brown pulp and paper industry as a whole there was an unutilized possibility of reducing CO_2, SO_2, and NO_x by 38, 28, and 27 percent (the average reduction potential compared to the observed average emission level), respectively, in 2008. This unutilized possibility of emission reduction corresponds to the percentage by which the industry actually could have increased environmental efficiency: $(1/0.623-1)\cdot 100 = 60.5$ percent.

Table 3a: Computed scores of relative environemental efficiency for Swedish pulp and paper firms in 2008 (brown firms)

	CO_2		SO_2		NO_x		EE
Firm	Observed emission (ton)	Reduction potential (ton)	Observed emission (ton)	Reduction potential (ton)	Observed emission (ton)	Reduction potential (ton)	
1	11307.3	0.00	15.42	0.00	18.06	0.00	1.000
2	28224.7	15021.49	33.34	17.74	22.22	11.83	0.468
3	1942.4	0.00	0.00	0.00	2.09	0.00	1.000
4	137.0	38.05	0.05	0.01	0.09	0.03	0.722
5	1137.7	165.36	0.02	0.00	1.02	0.15	0.855
6	19814.0	17696.99	22.84	20.40	15.74	14.06	0.107
7	4354.6	3858.19	3.71	3.29	3.23	2.87	0.114
8	10974.9	9658.69	6.33	5.57	10.96	9.65	0.120
9	9019.6	7647.90	6.20	5.26	7.45	6.32	0.152
10	1957.4	0.00	2.31	0.00	1.54	0.00	1.000
11	713.7	0.00	0.00	0.00	0.64	0.00	1.000
12	167.2	0.00	0.00	0.00	0.15	0.00	1.000
13	30981.1	22452.02	34.30	24.86	24.94	18.07	0.275
14	25303.0	0.00	29.83	0.00	19.92	0.00	1.000
15	130.3	117.21	0.04	0.04	0.09	0.08	0.101
16	1038.2	611.66	0.00	0.00	0.91	0.54	0.411
17	20629.4	0.00	24.37	0.00	16.24	0.00	1.000
18	16933.5	16255.23	10.34	9.92	16.62	15.95	0.040
19	218.6	0.00	0.07	0.00	0.15	0.00	1.000
20	54.0	0.00	0.00	0.00	0.06	0.00	1.000
21	19112.4	15692.57	4.20	3.45	19.53	16.03	0.179
22	13131.9	0.00	0.00	0.00	14.12	0.00	1.000
23	9654.2	0.00	11.40	0.00	7.60	0.00	1.000
24	126.3	101.91	0.04	0.03	0.09	0.07	0.193
25	31.9	20.57	0.01	0.01	0.02	0.01	0.356
26	135.7	90.30	0.05	0.03	0.09	0.06	0.334
27	93.1	0.00	0.03	0.00	0.06	0.00	1.000
28	29652.2	21854.61	13.22	9.74	43.66	32.18	0.263
29	1818.5	0.00	0.00	0.00	1.60	0.00	1.000
30	22.1	0.00	0.01	0.00	0.01	0.00	1.000
31	582.0	0.00	0.69	0.00	0.46	0.00	1.000
32	10421.8	8660.01	0.01	0.01	11.20	9.30	0.169
33	61.2	37.32	0.02	0.01	0.04	0.02	0.390
34	139.6	0.00	0.03	0.00	0.11	0.00	1.000
35	305.3	0.00	0.36	0.00	0.24	0.00	1.000
36	110.8	86.88	0.03	0.02	0.11	0.09	0.216
37	5268.0	4721.93	0.00	0.00	4.64	4.16	0.104
38	110408.0	0.00	141.56	0.00	266.21	0.00	1.000
39	23.9	0.00	0.01	0.00	0.02	0.00	1.000
40	316.9	0.00	0.00	0.00	0.28	0.00	1.000
41	7675.8	5857.29	0.02	0.01	8.23	6.28	0.237
42	19.0	11.91	0.00	0.00	0.02	0.01	0.373
Tot	394148.8	150658.07	360.84	100.41	540.45	147.75	0.623
		0.38		0.28		0.27	

As shown in Table 3b, environmental efficiency also varies considerably among green pulp and paper firms.

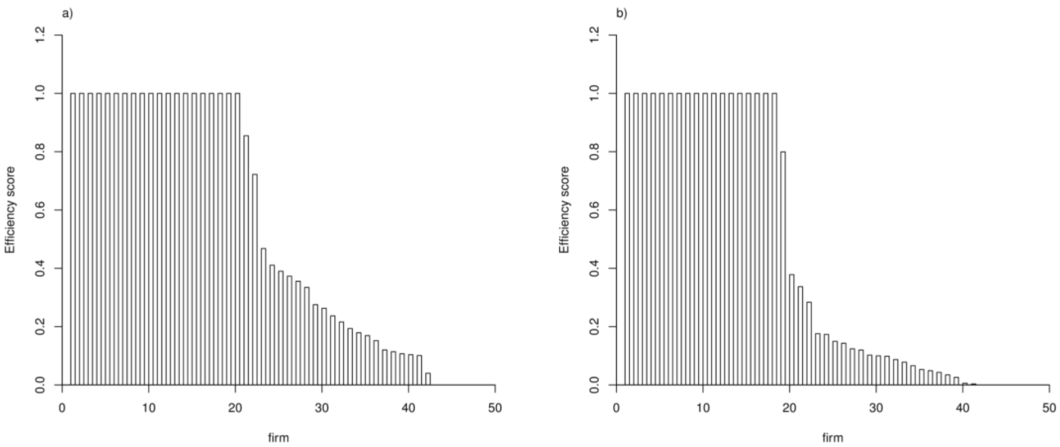
Table 3b: Computed scores of relative environemental efficiency for Swedish pulp and paper firms in 2008 (green firms)

	CO_2		SO_2		NO_x		EE
Firm	Observed emission (ton)	Reduction potential (ton)	Observed emission (ton)	Reduction potential (ton)	Observed emission (ton)	Reduction potential (ton)	
1	168367.5	144299.53	275.46	236.09	459.47	393.79	0.143
2	18596.0	17954.51	6.73	6.50	40.69	39.28	0.034
3	6588.0	6073.03	14.75	13.60	33.08	30.49	0.078
4	4881.4	0.00	22.78	0.00	71.92	0.00	1.000
5	15735.5	14697.00	26.23	24.50	43.53	40.66	0.066
6	47350.8	41680.18	67.66	59.56	127.58	112.30	0.120
7	103401.1	90594.85	154.54	135.40	228.07	199.82	0.124
8	42980.8	40885.01	77.51	73.73	142.18	135.25	0.049
9	39810.0	0.00	60.59	0.00	86.18	0.00	1.000
10	8394.6	0.00	40.31	0.00	140.75	0.00	1.000
11	11976.8	10799.90	23.11	20.84	45.83	41.32	0.098
12	228.5	205.72	0.06	0.06	0.17	0.15	0.100
13	19054.2	16202.74	35.17	29.91	71.15	60.50	0.150
14	124363.1	82468.16	212.56	140.95	363.11	240.79	0.337
15	155.9	0.00	0.05	0.00	0.10	0.00	1.000
16	1083.9	0.00	1.28	0.00	0.85	0.00	1.000
17	0.8	0.00	0.00	0.00	0.00	0.00	1.000
18	67609.6	60697.78	121.81	109.36	289.74	260.12	0.102
19	18.0	0.00	0.00	0.00	0.02	0.00	1.000
20	32634.5	0.00	26.92	0.00	108.46	0.00	1.000
21	39291.4	0.00	78.93	0.00	161.05	0.00	1.000
22	537.6	0.00	4.69	0.00	16.66	0.00	1.000
23	16.5	0.00	0.01	0.00	0.01	0.00	1.000
24	43130.0	42873.97	67.11	66.71	149.05	148.16	0.006
25	226.1	216.37	0.08	0.07	0.15	0.15	0.043
26	34634.3	32807.74	82.64	78.28	206.03	195.16	0.053
27	2.1	0.00	0.00	0.00	0.00	0.00	1.000
28	58621.7	48312.32	112.81	92.97	228.53	188.34	0.176
29	3601.1	2976.98	25.46	21.05	88.19	72.90	0.173
30	2.7	0.00	0.06	0.00	0.23	0.00	1.000
31	79.0	0.00	0.03	0.00	0.05	0.00	1.000
32	1831.5	1825.46	3.69	3.68	13.64	13.60	0.003
33	27.6	5.54	0.01	0.00	0.02	0.00	0.799
34	7830.4	4868.45	17.39	10.81	39.25	24.40	0.378
35	54.2	0.00	0.06	0.00	0.04	0.00	1.000
36	93.1	85.00	0.03	0.03	0.06	0.06	0.087
37	26.6	0.00	0.01	0.00	0.02	0.00	1.000
38	20.3	0.00	0.00	0.00	0.02	0.00	1.000
39	321.9	230.55	0.11	0.08	0.22	0.15	0.284
40	14788.7	0.00	29.72	0.00	60.67	0.00	1.000
41	1714.7	1670.55	8.41	8.20	27.75	27.04	0.026
Tot	920082.3	662431.35	1598.78	1132.36	3244.52	2224.46	0.523
		0.72		0.71		0.69	

For the green pulp and paper industry as a whole there was an unutilized possibility of reducing CO_2, SO_2, and NO_x with 72, 71, and 69 percent, respectively, in 2008. This unutilized possibility of emission reduction corresponds to the potential increase in environmental efficiency by $(1/0.523-1)\cdot 100=91.2$ percent. This result may seem counterintuitive but it may well be explained by the fact that environmental efficiency would increase by 91.2 percent if the firms almost entirely stop using fossil fuels in production and instead use non-fossil fuels. Note that some firms that constitute the technology frontier, and therefore serve as references for environmental efficiency (firms 17, 27, and 30), generate almost no emissions, as they use almost no fossil fuels.[9]

Figure 2a-b show the distribution of efficiency scores for green and brown firms, respectively. We can see that more brown firms are on the frontier (more scores close to 1), and that there seem to be more potential for green firms to improve (the score distribution tapers off faster for the green category). As we discussed above, this is owing to the fact that some firms in the green category use almost no fossil fuels (the main determinant of *EE*), which push the frontier far away from relatively fossil fuel intensive firms in the same category.

Figure 2a-b. Environmental efficiency scores estimated for firms in the Swedish pulp and paper industry in 2008: (a) brown firms, (b) green firms



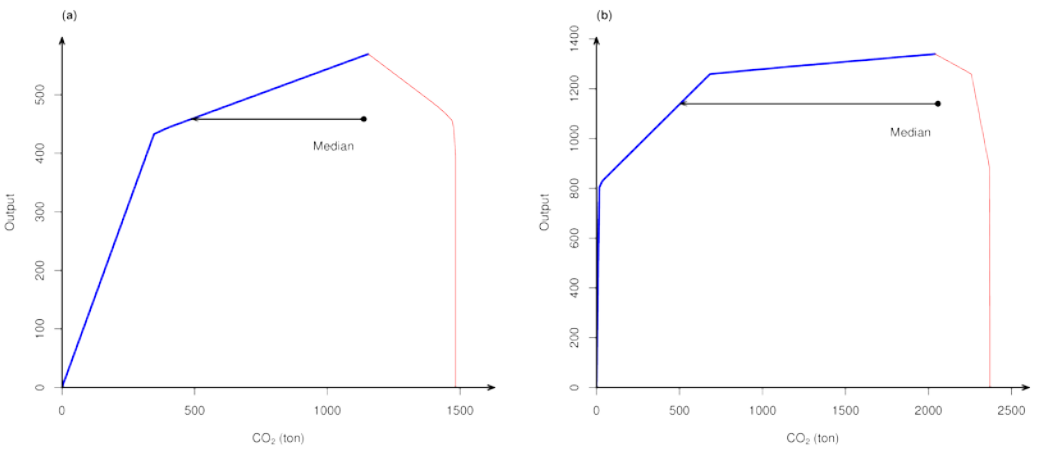
[9] This essentially means that if we would consider biomass fuels as not completely carbon neutral, then these frontier firms would have larger emissions and the potential efficiency improvement estimates for other firms would be lower. However, the data generating procedure at Statistics Swdeden does not count emissions from biofuels as they are considered carbon neutral.

In general, the environmental efficiency levels vary considerably among firms, no matter whether we study brown or green firms. Firms are either efficient (score = 1 for about half of the firms in both green and brown firms) or they are quite inefficient. This pattern is explained mainly by the extent to which firms use non-fossil fuels (electricity, biofuels, heat), compared to fossil fuels (coal, oil, gasoline) in production. In 2008 there was a substantial potential to "catch-up" among fossil fuel intensive firms by investing in the less fossil fuel demanding technologies used by the efficient firms.

4.2 Pollution Generating Technologies in Pulp and Paper

Figures 3a and 3b show the pollution generating technologies, in this case the output possibilities sets, $P(x)$, of the median brown and green firms, respectively (the median with respect to total energy use, i.e., nonfossil fuels + fossil fuels). These sets show all the feasible combinations of the marketable product and emissions that can be produced, given the frontier technology and the median firm's input use in production. Specifically, by using the optimizing problem in Equation (3), the sets are simulated for the marketable product and CO_2 space.

Figure 3a-b. The pollution generating technology in terms of the output possibility set, simulated for the median firm in the Swedish pulp and paper industry in 2008: (a) the brown firm, (b) the green firm.



A reflection is that the simulated output sets in Figures 3a and 3b satisfy the axioms of production technology (in the green case it may seem that the axiom of good and bad outputs being null-joint is violated, but it is not). Most importantly, confirming the results discussed above, Figure 3a-b illustrates that not only could the median brown firm have been more environmentally efficient in 2008, but also the median green firm. Also, as earlier concluded, the potential of becoming more environmentally efficient is larger for the median green firm. In this case, there are firms with very low emission levels (using small quantities of fossil fuels) that shape the technology frontier, and to which many of the other firms are compared.

Finally we look at environmental efficiency among different sectors in the Swedish manufacturing industry.

4.3 Environmental Efficiency in Swedish Manufacturing

Assessing the environmental efficiency in Swedish manufacturing reveals considerable variation in efficiency among sectors. In the brown subsectors environmental efficiency ranges between 0.314 and 0.731. The highest efficiency score is found in printing with the possibility of increasing efficiency with $(1/0.731-1)\cdot 100 = 36.8$ percent. In this case the unutilized possibility of reducing CO_2, SO_2, and NO_x is 29, 24, and 29 percent, respectively. The lowest environmental efficiency score is found in Food with a possible $(1/0.314-1)\cdot 100 = 218.5$ percent increase in environmental efficiency. Assuming that firms maximize profits this indicates that firms are more heterogeneous in their polluting generating technologies in Food, compared to firms in Printing, and therefore there is a substantial "catching-up" potential of reducing emissions.

Table 4a: Computed scores of environmental efficiency for Swedish manufacturing industry in 2008 (brown firms).

	N	CO_2			SO_2			NO_x			EE		
		observed (ton)	Reduction (ton)	p	observed (ton)	reduction (ton)	p	observed (ton)	reduction (ton)	p	mean	min	max
Mining	11	700533.2	2975.8	0.000	781.26	1.00	0.000	3462.97	2.00	0.000	0.731	0.002	1.000
Food	124	322075.7	266687.8	0.830	106.20	71.15	0.670	275.02	230.67	0.840	0.314	0.010	1.000
Textile	29	32061.5	17142.1	0.530	16.16	6.30	0.390	27.52	14.37	0.520	0.664	0.019	1.000
Wood	76	30163.3	21310.6	0.710	33.97	25.78	0.760	59.34	41.59	0.700	0.524	0.019	1.000
Pulp/paper	42	394148.8	150658.1	0.380	360.84	100.41	0.280	540.45	147.75	0.270	0.623	0.040	1.000
Printing	29	9912.3	2849.7	0.290	0.65	0.16	0.240	9.74	2.84	0.290	0.731	0.047	1.000
Chemical	50	240128.1	54327.7	0.230	129.04	18.92	0.150	197.61	45.40	0.230	0.590	0.019	1.000
Rubber/plastic	67	63259.8	47836.2	0.760	9.80	6.05	0.620	55.15	41.83	0.760	0.523	0.014	1.000
Stone/mineral	52	1207852.7	334513.4	0.280	588.89	221.93	0.380	2326.43	419.63	0.180	0.576	0.003	1.000
Iron/steel	19	3087852.3	376852.1	0.120	15664.46	184.31	0.010	8649.46	373.95	0.040	0.659	0.100	1.000
Metal	143	23864.8	17878.3	0.750	4.81	3.29	0.680	21.06	15.69	0.740	0.334	0.001	1.000
Machinery	164	37889.8	23469.0	0.620	10.75	8.29	0.770	30.06	17.19	0.570	0.341	0.014	1.000
Electro	43	13191.9	6782.5	0.510	3.57	1.63	0.460	10.63	5.14	0.480	0.591	0.061	1.000

Vehicles	57	77199.7	9231.8	0.120	158.06	2.63	0.020	94.49	7.48	0.080	0.586	0.013	1.000
Industry	906	6240133.9	1332515.0	0.214	17868.46	651.85	0.036	15759.93	1365.55	0.087			

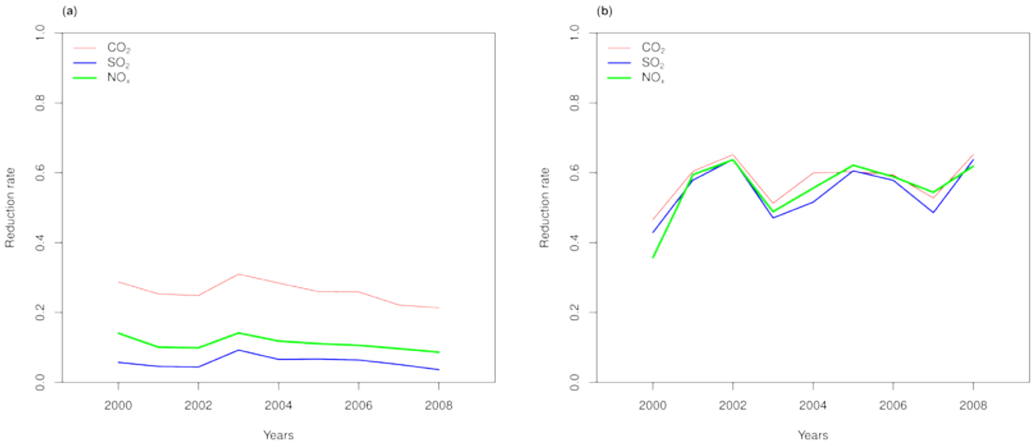
As is shown in Table 4b the difference among green subsectors is also considerable. In this case environmental efficiency ranges between 0.194 and 0.825. The highest efficiency score is found in Iron/Steel with the possibility of increasing efficiency with $(1/0.821-1)\cdot 100 = 21.2$ percent. In this case the unutilized possibility of reducing CO_2, SO_2, and NO_x is 31, 5, and 33 percent, respectively. The lowest environmental efficiency score, 0.194, is found in Machinery.

Table 4b: Computed scores of environmental efficiency for Swedish manufacturing industry in 2008 (green firms)

	N	CO_2			SO_2			NO_x			EE		
		observed (ton)	Reduction (ton)	p	observed (ton)	reduction (ton)	p	observed (ton)	reduction (ton)	p	mean	min	max
Mining	13	2420.4	2081.6	0.860	0.81	0.70	0.860	1.82	1.40	0.770	0.706	0.008	1.000
Food	124	114803.0	93166.7	0.810	72.45	55.45	0.770	157.50	138.55	0.880	0.284	0.001	1.000
Textile	30	3733.3	1702.1	0.460	0.52	0.43	0.810	3.07	1.32	0.430	0.511	0.011	1.000
Wood	76	20100.1	16468.6	0.820	229.88	130.57	0.570	876.89	484.89	0.550	0.399	0.001	1.000
Pulp/paper	43	947621.2	662431.3	0.700	1676.54	1132.36	0.680	3447.27	2224.46	0.650	0.523	0.003	1.000
Printing	30	1342.1	282.1	0.210	0.36	0.09	0.260	1.12	0.19	0.170	0.814	0.008	1.000
Chemical	50	222305.6	102568.1	0.460	105.64	18.85	0.180	239.99	91.01	0.380	0.685	0.000	1.000
Rubber/plastic	68	8880.4	6120.7	0.690	2.79	1.82	0.650	6.35	4.35	0.680	0.563	0.014	1.000
Stone/mineral	53	16512.0	9870.4	0.600	6.04	2.38	0.390	12.67	7.94	0.630	0.525	0.001	1.000
Iron/steel	19	33940.5	10637.4	0.310	2.33	0.12	0.050	34.74	11.30	0.330	0.825	0.136	1.000
Metal	144	7561.0	6196.0	0.820	2.08	1.37	0.660	6.63	5.17	0.780	0.341	0.001	1.000
Machinery	165	31996.9	29025.7	0.910	6.33	4.85	0.770	30.67	28.16	0.920	0.194	0.000	1.000
Electro	44	15009.1	13430.1	0.890	4.52	4.03	0.890	10.73	9.56	0.890	0.389	0.006	1.000
Vehicles	58	58040.2	14175.6	0.240	22.16	6.89	0.310	49.12	11.81	0.240	0.468	0.006	1.000
Industry	917	1484265.8	968156.4	0.652	2132.46	1359.91	0.638	4878.58	3020.12	0.619			

So far we have studied environmental efficiency in the Swedish manufacturing industry in 2008, with focus on the Pulp and paper industry. However, it is also interesting to study the development of environmental efficiency over time. This is shown in Figure 4, where the reduction rate (the ratio of unutilized possibility of emission reduction to observed emission) is plotted for the years 2000 to 2008.

Figure 4. Potential reduction rate of emissions in Swedish manufacturing industry; (a) brown firms, (b) green firms



Potential emission reductions compared to the actual emissions have decreased among brown firms during the period. Assuming profit maximization this mean that brown firms have become more homogeneous in polluting generating technologies. Among green firms the trend is not obvious.

5 Conclusions and discussion

The main purpose of this paper has been to study environmental efficiency among brown and green firms within Swedish manufacturing industry, with special focus on the pulp and paper industry in 2008. We argue that, irrespective of firms being considered as brown or green, firms' production technology should be seen as a pollution generating technology, which theoretically is modeled by imposing the technological axioms of good and bad outputs being null-joint and together weakly disposable. Hence, good and bad outputs are produced simultaneously.

Similar to Picazo-Tadeo and Garcia-Reche (2007), we measure environmental efficiency as firms' potential to reduce production of bad outputs, given technology and inputs used in production. This means that environmental performance is assessed by only crediting reduction in emissions. Environmental efficiency scores are computed by applying the DEA model as a pollution generating technology.

The general results are that there is considerable variation in environmental efficiency among firms in the pulp and paper industry, but also among sectors in Swedish manufacturing. That is, among both brown and green firms there was a considerable unutilized potential of reducing emissions in 2008 given technology and input use. This is also in line with Picazo-Tadeo and Garcia-Reche (2007), find considerable potential for improving environmental efficiency among different firm characteristics. Also, the result shows that the potential for reducing emissions decreased moderately during 2000 to 2008, indicating that environmental efficiency among firms somewhat improved.

From a policy point of view the results are interesting. Not only are there considerable improvements among firms in general to be made without sacrificing output (“low hanging fruit”), but these improvements exist also within the green and relatively clean category of firms. That is, when designing policy to reduce emissions, one should not only focus on the dirty firms, but also include the relatively clean firms.

Finally, in the data we use in this study, biofuels are assumed carbon neutral and do not contribute at all to carbon emissions, which is true in the long run, but questionable in the short run. Therefore, the estimated technological frontier will be shaped by firms using relatively small amounts of fossil fuels in production, to which the rest of the firms will be compared. As the use of non-fossil fuels, e.g., biofuels, actually releases carbon emission, the potential of reducing CO_2 can be overestimated. As a consequence the assumption of carbon neutrality may then cause misleading policy implications regarding the actual potential of reducing CO_2. For a discussion on the assumption of carbon neutrality and its consequences for climate policy and on what is sometimes referred to as a “carbon accounting error”, see Lundgren and Marklund (2012a, 2012b), Cherubini et al. (2011), and Searchinger et al. (2009).

6 References

Baumgärtner, Stefan, Harald Dyckhoff, Malte Faber, John Proops Johannes Schiller. 2001. “The concept of joint production and ecological economics.” *Ecological Economics* 36(3):365–372.

Brännlund, R., T. Lundgren and P-O. Marklund (2011) Environmental Performance and Climate Policy. Centre for Environmental and Resource Economics, CERE Working paper, 2011:6, Department of Economics, Umeå University.

Cherubini, F. G.P Peters, T. Berntsen, A.H. Strømman and E. Hertwich (2011) CO2 Emissions from Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming. GCB Bioenergy, doi: 10.1111/j.1757-1707.2011.01102.x.

Chung, Y.H., R. Färe and S. Grosskopf (1997) Productivity and Undesirable Outputs: A Direcetional Distance Function Approach. *Journal of Environmental Management*, 51(3): 229-240.

Färe, R. S. Grosskopf. 2004. *New directions: efficiency and productivity*. Kluwer Academic Publishers, Boston.

Färe, R., S. Grosskopf and F. Hernandez-Sancho (2004) Environmental Performance: An Index Number Approach. Resource and Energy Economics, 26(4): 343-352.

Färe, R., S. Grosskopf and C. Pasurka (1986) Effects on Relative Efficiency in Electric Power Generation due to Environmental Controls. *Resources and Energy*, 8(2): 167-184.

Färe, R., S. Grosskopf and C.A. Pasurka, Jr. (2001) Accounting for Air Pollution Emissions in Measures of State Manufacturing Productivity Growth. *Journal of Regional Science*, 41(3): 381-409.

Färe, R., S. Grosskopf and C.A. Pasurka Jr. (2006) Social Responsibility: U.S. Power Plants 1985-1998. Journal of Productivity Analysis. 26(3): 259-267.

Färe, R., S. Grosskopf and C.A. Pasurka Jr. (2010) Toxic Releases: An Environmental Performance Index for Coal-fired Power Plants. Energy Economics, 32(1): 158-165.

Färe, R., S. Grosskopf and D. Tyteca (1996) An Activity Analysis Model of the Environmental Performance of Firms – Application to Fossil-fuel-fired Electric Utilities. *Ecolocical Economics*, 18(2): 161-175.

Färe, Rolf, Shawna Grosskopf, C. A. K. Lovell Carl Pasurka. 1989. "Multilateral Productivity Comparisons When Some Outputs are Undesirable: A Nonparametric Approach." *The Review of Economics and Statistics* 71(1):90–98.

Färe, R., S. Grosskopf, T. Lundgren, P-O. Marklund and W. Zhou (2012) Productivity: Should we Include Bads? Centre for Environmental and Resource Economics (CERE), Working paper, 2012:13, Department of Economics, Umeå University.

Jeon, B.M. and R.C. Sickles (2004) The Role of Environmental Factors in Growth Accounting. *Journal of Applied Econometrics*, 19(5): 567-591.

Kemeny, John G., Oskar Morgenstern Gerald L. Thompson. 1956. "A Generalization of the von Neumann Model of an Expanding Economy." *Econometrica* 24(2):pp. 115–135.

Kumar, S. (2006) Environmentally Sensitive Productivity Growth: A Global Analysis using Malmquist-Luenberger Index. *Ecological Economics*, 56(2): 280-293.

Lundgren, T. and P-O. Marklund (2012a) Assessing the Welfare Effects of Promoting Biomass Growth and the Use of Bioenergy. Forthcoming in *Climate Change Economics*.

Lundgren, T. and P-O. Marklund (2012b) Bioenergy and Carbon Neutrality. Journal of Forest Economics 18, 175-176.

Lundgren, T. and P-O. Marklund (2012) Environmental Performance and Profits. Centre for Environmental and Resource Economics, CERE Working paper, 2012:8, Department of Economics, Umeå University.

Malmquist, S. (1953) Index Numbers and Indifference Surfaces. Trabajos de Estadistica, 4: 209-242.

Picazo-Tadeo, A.J., A. García-Reche (2007). What makes environmental performance differ between firms? Empirical evidence from the Spanish tile industry. *Environment and Planning A* 39(9), 2232 – 2247

Searchinger, T.D, S.P. Hamburg, J. Melillo, W. Chameides, P. Havlik, D.M. Kammen, G.E. Likens, R.N. Lubowski, M. Oberstainer, M. Oppenheimer, G.P. Robertson, W.H. Schlesinger, and G.D. Tilman (2009) Fixing a Critical Accounting Error. *Science* 326(5952), 527-528.

Shephard, Ronald William. 1970. *Theory of cost and production functions, by Ronald W. Shephard*. Princeton studies in mathematical economics; no. 4 Princeton, N.J.: Princeton University Press.

Shephard, R.W. R. Färe. 1974. “The law of diminishing returns.” *Zeitschrift fur Nationalokonomie* 34:69–70.

von Neumann, J. V. 1945. “A Model of General Economic Equilibrium.” *The Review of Economic Studies* 13(1):pp. 1–9.

Tyteca, D. (1997) Linear Programming Models for the Measurement of Environmental Performance of Firms – Concepts and Empirical Results. *Journal of Productivity Analysis*, 8(2): 183-197.

Weber, W.L. and B. Domazlicky (2001) Productivity Growth and Pollution in State Manufacturing. *Review of Economics and Statistics*, 83(1): 195-199.

Yu, M-M., S-H. Hsu, C-C. Chang and D-H. Lee (2008) Productivity Growth of Taiwan’s Major Domestic Airports in the Presence of Aircraft Noise. *Transportation Research Part E, Logistics and Transportation Review*, 44(3): 543-554.

Yörük, B.K. and O. Zaim (2005) Productivity Growth in OECD Countries: A Comparison with Malmquist Indices. *Journal of Comparative Economics*, 33(2): 401-420.