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Environmental Efficiency, Separability and Abatement Costs of Nonpoint-source Pollution

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Abstract

This paper presents a new framework for analyzing abatement costs of nonpoint-source pollution. Unlike previous studies, this framework treats production and pollution as non-separable and also recognizes that production inefficiency is a fundamental cause of pollution. The implications of this approach are illustrated using an empirical analysis for cotton producers.

1. Introduction

The marginal abatement cost (MAC) curve links a firm's emission levels and the cost of additional units of emission reduction. The conventional theory bases the MAC curve on two (implicit) assumptions: that production and abatement are separable and that present production is efficient. Separability means that emission control is a function of emissions alone, the production side is ignored in the assessment of the abatement costs. Based on this assumption, the abatement cost curve emphasises that a firm can control its emission only by either investing in pollution control equipment or by reducing output. Based on separability and efficiency, the MAC is downwards sloping and always positive – pollution control is always costly.

The MAC is a key tool in environmental economics but its properties are seldom explored[i]. Particularly the aforementioned properties have not been related to recent work on environmental (in) efficiency. Besides, attention in the latter literature focuses primarily on empirical methods and applications, not on the theoretical implications for abatement costs. Compelling reasons have been presented for accommodating productive inefficiency in estimations of profit function (Kumbhakar, 2001). For abatement cost functions this issue has not yet been addressed.

This paper develops an externality production model that blends the theory of productive efficiency with the concept of marginal abatement cost. The connecting principle is the non-separability of output and pollution abatement.

The outline of the paper is as follows. First, we provide a critique on the traditional literature on abatement costs. Second, a theoretical model of the farm is presented in which pollution is a joint output of production and inefficiency in production prevails. Third, our conceptual model is implemented by means of Data Envelopment. We model environmental effects as conventional inputs. This approach provides separate estimates of environmental efficiency and cost efficiency from which the marginal abatement costs are then derived. High quality survey data for a sample of 275 cotton producers collected as part of the 2000 Upland Cotton Production Practices Report are used for a case study assessment.

2. A critique on the traditional literature of abatement cost

Our critique on the conventional view is threefold and relates to agro-ecosystem management, insights provided by the literature of technical and environmental efficiency, and the process of environmental economic adjustments at the farm level

Firstly, the conventional assumptions of the MAC do not adequately describe the technical management side to emission control. Production, pollution and abatement are to be treated as *non-separable* to include control options provided by changes in production practices. Besides, non-separability enables proper account to be taken of the material flow through production processes (Wossink *et al*., 2001). Production externalities most often result from specific inputs that have the characteristics of joint inputs, as any quantity simultaneously produces the intended agricultural output and the unintended externality. The combination in which these marketable outputs and bad side effects is generated depends on the production method chosen – this combination is not fixed. Generally, several production methods are available that vary both in their costs and in their environmental impacts. Agronomic research shows that there exists a tremendous range of proven alternative methods in agricultural production that have the potential to reduce pollution at source by increasing the efficiency of input-use (Khanna and Zilberman, 1997).

Secondly, there is an extensive *literature on productive efficiency* that has extended the basic neo-classical approach by allowing producer to make mistakes in the production of outputs and the use of inputs. Fare *et al.* (1993) introduced negative environmental effects in the output distance function of the economic efficiency literature. The output distance function is dual to the revenue function, and marginal abatement costs are theoretically derived from the dual relationship. This approach considers emissions as undesirable outputs or by-products that are a direct function of the producing firm's output. In other words, a certain percentage reduction in emission can only be achieved by the same percentage reduction output, which by definition makes pollution abatement costly. Recent applied work on environmental efficiency has taken another perspective (see Reinhard *et al*., 2000). Similar to conventional inputs, emission inputs can be considered as strongly disposable[ii]. The latter implies that environmental improvement can be achieved by fine-tuning input levels and input mixes and this does not have to come at a private cost. In contrast, higher levels environmental efficiency might be associated with higher levels of financial returns.

Finally, the conventional assumptions underlying abatement cost analysis do not adequately describe the *process* of farm level transition to environmentally sound production practices and how this influences abatement costs. Hill *et al*. (1999) distinguish three main stages[iii] in this process: (1) efficiency improvement, (2) substitution of inputs or production processes and (3) redesign, that is output reduction or the use of new or additive technology for environmental purposes. Abatement costs studies generally focus on the latter stage, that is on the cost associated with reducing output or with direct outlays of capital and operating expenditures for additive technology. In practice producers confronted with an environmental regulation, will first try to reduce pollution at source by either efficiency improvement of input use or by substitution of productive inputs or production processes. The first measures a farmer will implement will be simple and cheap, and have low risk. These measures are of an operational nature and come down to more accurate management, which will improve the environmental efficiency of the farming system and can improve financial results as well[iv]. When these measures do not suffice to meet the environmental regulation, farmers will resort to decision on a tactical level, like a change to a resistant or tolerant cultivar. The tactical measures have more significant effects on the financial results of the farm and will be more risky. If further reductions are necessary, changes on a more strategic level may be considered such as changing the rotation, which means a reduction in output level.

3. Theoretical model

For an assessment of the costs of abatement of non-point source pollution, complete information is required on the production structure and the production relationships involved, including a measure of damage, the possibilities of input substitution and changes in the proportion of intended outputs and side-effects. In order to capture this information, the analysis should be performed at the disaggregate level that permits the contribution from intermediate inputs, including the biological and physical inputs to be identified. Besides, economic specifications for incorporating the agriculture-environment interactions should have the capability of integrating the biological and physical processes in a manner consistent with agronomic insights.

The generalised joint production model by Sudit and Whitcomb (1976) allows the incorporation of input-output relations based on agronomic knowledge in economic models (Archibald, 1988; De Koeijer *et al*., 1999). As well as incorporating agronomically based input-output relationships, the model allows: (a) intended outputs and externalities to be produced, (b) the proportion of these outputs to be varied, and (c) possibilities of rearrangement of productive input to counter externalities. Omitting the time aspect, the model for the situation in which a farmer produces one output, *y*, and generates only one environmental effect, *z*, can be written as (Wossink *et al*., 2001):

$$y = f_1(V \;;D) \qquad (1a)$$
$$V = f_2(V_0, X; D) \qquad (1b)$$
$$z = g_1(W; D) \qquad (1c)$$
$$W = g_2(W_0, X; D) \qquad (1d)$$

or: $$y = F(V_0, X; D) \text{ with } F = f_1(f_2(.); D) \qquad (2a)$$
$$z = G(W_0, X; D) \text{ with } G = g_1(g_2(.); D) \; y = F(V_0, x; D) \qquad (2b)$$

where V is a vector of growth limiting and reducing factors (incidence of weeds, pests, diseases; water and nutrient shortage; low soil organic matter); V_0 is a vector of the untreated levels of the growth limiting and reducing factors; X is a vector of variable inputs to control these factors, and D is a vector of growth determining factors (crop characteristics, soil characteristics and climatic factors). Further z is an environmental effect of agricultural production and W is a vector of environmental impact factors (*viz.*, pesticide runoff and nitrate and phosphorus surplus). W_0 denotes the level of the environmental impact factors before the specific agricultural activity characterized by X and y.

In eqn. *(2a)* the vector X acts indirectly on output y through a change in the growth reducing and limiting factors V_0 (cf. Chambers and Lichtenberg, 1994; 1996). Compared to the impact of input on output, the impact of inputs X on z is even more indirect, see eqn. *(2b)*.

Production activities lead to a change in the environmental impact factors, W_0, and this causes the ultimate environmental effect z.

Next, we consider input saving technical efficiency by replacing X by $Xe^{\eta}(\eta \leq 0)$. Thus, for an inefficient farm, actual input quantities used (X) are more than the minimum of required (Xe^{η}) to produce a given level of y (Kumbhakar, 2001). Consequently η is interpreted as the rate at which use of all the inputs could be reduced without reducing the output when inefficiency is eliminated (radial measure of technical inefficiency).

In the above presentation, it has been assumed for simplicity that the production method is given. To introduce alternative technologies, let ϕ be a production method with $\phi \in \Phi$, where Φ is the technology set for the output considered.

Summarizing the aspects above, the cost minimizing values of X and z are found through minimizing the direct cost function subject to a fixed output, y^0, and a constraint on pollution z^r:

$$Min_{X,z} \quad C = p\ Xe^{\eta} - c_{\phi} | \ \phi \qquad (3a)$$

$$s.t. \quad F(y^0, V_0, Xe^{\eta}; D) - y^0 = 0 \qquad (3b)$$

$$G(z, W_0, Xe^{\eta}; D) - z^r = 0 \qquad (3c)$$

where the optimal cost is *conditional* on the production technology chosen. The fixed costs of the technology are denoted as c_{ϕ} and the price of the inputs is denoted as p. First order conditions for an optimal solution are given by:

$$-pe^{\eta} + \lambda_1 \frac{\partial F}{\partial Xe^{\eta}} + \lambda_2 \frac{\partial G}{\partial Xe^{\eta}} = 0 \qquad (4)$$

$$\lambda_2 \frac{\partial G}{\partial z} = 0 \qquad (5)$$

$$F(y^0, V_0, Xe^{\eta}; D) - y^0 = 0 \qquad (6)$$

$$G(z, W_0, Xe^{\eta}; D) - z^r = 0 \qquad (7)$$

The use of the envelope theorem gives the expression for the marginal costs:

$$\frac{\partial C^*}{\partial y^0} = \lambda_1^* + \lambda_2^* \qquad (8)$$

The marginal costs consist of two parts, a production driven component, λ_1^*, and a pollution restriction based component, λ_2^*. From the FOC we can formulate λ_2^* as:

$$\lambda_2^* = \frac{pe^{\eta} - \lambda_1^* \dfrac{\partial F}{\partial(X^* e^{\eta})}}{\dfrac{\partial G}{\partial(X^* e^{\eta})}} \qquad (9)$$

which shows the marginal benefit to the producer of generating one more unit of pollution *z*. Notice that this is equivalent to the marginal abatement cost.

Eqn. *(9)* shows that pollution (or pollution abatement for that matter) and production cannot be treated as separable. Formulations that impose separability ignore the term $\frac{\partial G}{\partial(X^* e^{\eta})}$ and assume that the optimal level of input use and the production technique chosen are independent of the pollution level and pollution limit. Eqn. *(9)* also shows that only if production *F(·)*, and pollution *G(·)*, are homogenous (constant returns to scale) is the marginal abatement cost independent of technical inefficiency in production. The extent in which marginal abatement cost is affected is an empirical issue.

4. Empirical assessment for pesticide use in cotton

4.1 Background and method

Historically, most pest control efforts in cotton have sought to find single, simple, direct interventions that quickly reduce the pest population(s) below an acceptable level by means of conventional prophylactic, calendar-based use of broad-spectrum pesticides. These interventions are not necessarily optimised from an economic point of view and they are definitely not optimised from an environmental point of view. Integrated pest management (IPM) aims at improving the accuracy and timing with which pesticides are applied and promotes benign substitutes such as less harmful pesticides, biological controls and changes in planting date, rotation and conservation tillage[v]. Modern biotechnology has further enlarged the spectrum of pest controls in cotton production. Transgenic insect-resistant and herbicide tolerant cotton varieties were developed that enable growers to use in-plant protection methods as part of integrated pest management programs. In summary, cotton producers can alter externality levels of pest control by varying input levels, input mixes or methods of production. Producers' efficiency in applying the control methods further affects returns and environmental impacts.

The case of pest control in cotton is used to quantify technical efficiency, environmental efficiency and cost efficiency. Environmental efficiency is defined a the ratio of minimum feasible to observed use of environmentally detrimental inputs per unit output measured in terms of their environmental impacts, conditional on the non-detrimental inputs used for pest control. The marginal abatement costs are derived from the cost efficiency and environmental efficiency results.

Technical, environmental, cost and abatement cost efficiency of conventional or genetically modified (for example herbicide resistant) cotton production is determined for each grower separately using the farms with the same technology as the reference group. Overall efficiencies are determined by using all growers (all technologies) as the reference group. Productivity is determined as the ratio of efficiency relative to the own reference group and this efficiency relative to the overall frontier, for each grower.

The non-parametric DEA method[vi] was used to compute the input-based overall technical and environmental efficiency. Important characteristics of DEA over the alternative parametric SFA approach are: (1) no a-priori specification of the technology, and (2) the ability the test for returns to scale.

4.2 Data

The data used in the DEA analysis were collected after the 2000 season as part of the Upland Cotton Production Practices Report survey by the USDA-NASS. A total of 275 North Carolina cotton producers were interviewed. After removing incomplete questionnaires, 202 remained for analysis. The data used are from an entire growing season. Table 1 presents summary statistics of the variables used in the analysis. As Table 1 shows, the data set consists of one output, five environmentally detrimental inputs and three non-environmental detrimental inputs for pest control and the cost of pest control. Three technologies were distinguished: herbicide tolerant, stacked gene (herbicide tolerant and insect resistant) and conventional.

The inputs are all aggregated measures. Chemical pest control is represented by herbicides, insecticides, growth regulators and defoliants and is measured in dollars per acre.

The environmental impact of these pesticides is proxied through the pounds of active ingredient (a.i.) applied. The non-detrimental inputs were quantified through a factor analysis of the 89 field characteristics in the Upland Cotton Production Practices Report survey. We determined three main composite factors related to pest control: "Formal plans for pest, nutrient and conservation management"; "Crops planted on specific field in previous years", and "Timing of planting and harvesting". The minimum observed factor score was subtracted from the values for observation to assure positive values. The resulting translated factor scores were used as input values for the non-environmental detrimental inputs.

Cost of pest control is composed of the cost for the five categories of pesticides and a technology fee if genetically modified cottonseed is used. For herbicide tolerant $9 and for stacked gene cotton $ 38 per acre was used as no grower specific information was available from the survey.

5. Results

5.1 Efficiency and productivity scores

The efficiency and productivity measures were estimated in OnFront (Färe and Grosskopf, 2000). Efficiency and productivity scores were computed as described in section 4.2 and are presented in Table 2.

Table 2 shows that technical efficiency of pest control under constant returns to scale (CRS) is higher for growers of conventional cotton than for growers of herbicide tolerant and stacked gene cotton (0.86 versus 0.76 and 0.80). A similar result holds for technical efficiency and environmental efficiency under variable returns to scale (VRS). The comparison of the technical efficiency scores for non-increasing returns to scale (NIRS) and VRS shows that on average farmers are producing in the region of decreasing returns to scale. This applies to growers of herbicide tolerant and stacked gene cotton, in particular.

The environmental efficiency scores relative to the own frontier are comparable to the technical efficiency scores, except for conventional growers for which the environmental efficiency score is lower. Growers of conventional cotton could reduce the environmental impacts of pest control relative to their own frontier (VRS), on average by 18 per cent, whereas for growers of herbicide tolerant and stacked gene cotton this is 21 and 19 percent, respectively. The overall environmental efficiency scores are low in comparison with these scores relative to the technology specific frontier, which shows that the variability in environmental efficiency between technologies is larger that the variability within these technologies.

The productivity measures show that, although growers of conventional cotton are using a less productive technology then growers of stacked gene and herbicide tolerant cotton, they producing more technically efficiently relative to their own frontier. The (technical) productivity VRS of stacked gene cotton is 0.95 whereas this is 0.84 and 0.80 for herbicide tolerant and conventional cotton, respectively.

Whereas stacked gene cotton is most efficient from the technical and environmental point of view, the opposite applies with respect to cost efficiency. Overall cost efficiency is only 0.23 for stacked gene cotton; for both conventional and herbicide tolerant cotton this is 0.33.

5.2 Marginal abatement costs

The results in Table 2 show that inefficiency is considerable and that variable returns to scale prevail both in production and in pollution generation. As discussed in section 3, in this situation marginal abatement costs will be affected.

To assess the compatibility of improvements in environmental and economic performance, we calculated the overall abatement cost efficiency for each producer using the VRS environmental and cost efficiency scores (both ranging between 0 and 1). The results are presented in Table 3. The mean abatement cost efficiency for all producers was 0.54 and of the 202 cotton producers, 175 could potentially improve both their economic and environmental performance.

Herbicide tolerant and conventional producers could on average improve their environmental and cost efficiency by 14 and 17 per cent compared to efficient colleagues using the same technology. Growers of stacked gene cotton are more efficient compared to their own frontier (0.88) and also have the highest score compared to the overall frontier (0.60).

The technology-specific mean scores translate to an average negative marginal abatement cost of $1.20, $11.86 and $12.18 per pound of active ingredient for conventional, herbicide tolerant and stacked gene cotton, respectively.

6. Conclusion and discussion

In this paper we have presented a framework for analyzing abatement costs of nonpoint-source pollution that treats production and pollution as non-separable and also recognizes that production inefficiency is a fundamental cause of pollution. Efficiency is determined by the (outermost) production possibility frontier, which is determined by the state of technology. Our theoretical model shows that both substitution of inputs and environmental efficiency improvements can offset (part of) the costs associated with better environmental quality of agricultural production.

Cost efficiency and environmental efficiency scores were assessed for a sample of 202 cotton producers in North Carolina. Environmental effects were modelled as conventional inputs. Calculating the abatement cost efficiency score for each grower assessed the compatibility of environmental and cost efficiency.

Further research could focus on the measure for environmental impacts. The metric used for pesticides (a.i. applied) assumes that environmental damage is directly correlated with the quantity of pesticide use, regardless of the specific chemical and formulation. Instead damages can be measured through changes in the relative risks to a series of human and environmental health risks (Brethour and Weersink (2001: 220).

In the paper we have addressed the total of pesticides. Sub-vector efficiency, productivity and abatement cost efficiency by pesticide category could be determined in a similar way.

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Table 1 Summary statistics of the data used

Variable	*Units*	*Seed type*					
		Herbicide tolerant (n=74)		Stacked-gene (n=79)		Conventional (n=49)	
		mean	s.d.	mean	s.d.	mean	s.d.
Output: Lint yield	Lbs./acre	785.58	142.12	790.81	144.09	801.24	151.06
Pesticide use:							
• Insecticides	$/acre	19.58	9.89	18.30	19.22	20.92	15.22
• Herbicides		16.49	9.99	12.79	11.72	22.28	13.34
• Fungicides		0.20	1.41	0.64	2.85	6.27	41.02
• Growth reg.		15.91	9.81	15.69	11.04	18.06	4.59
• Defoliants		4.63	4.64	4.91	6.25	9.13	9.92
Non-detrimental inputs for pest control:							
• "Formal plans for pest, nutrient and conservation management"	Factor scores	1.22	1.15	1.21	0.93	1.15	0.92
• "Crops planted on specific field in previous years"		3.51	1.16	3.57	0.93	3.60	0.89
• "Timing of planting and harvesting"		4.95	0.94	4.67	0.92	4.73	1.20
Env. detrimental effects of pest control:							
• Insecticides	Lbs. a.i./acre	0.50	0.35	0.50	0.43	0.51	0.34
• Herbicides		2.09	1.33	1.64	1.28	2.98	1.78
• Fungicides		0.05	0.22	0.05	0.19	0.04	0.16
• Growth reg.		1.70	1.86	1.45	1.74	2.12	1.97
• Defoliants		0.49	0.68	0.56	0.75	0.36	0.46
Total costs of pest control	$/acre	65.85	22.91	89.14	30.91	72.13	47.02

Table 2 Mean[1] efficiency and productivity scores of herbicide tolerant, stacked gene and conventional cotton production

Performance measure by technology	Cost Eff. of pest control	Technical Efficiency of pest control			Environmental Efficiency of pest control		
		CRS	NIRS	VRS	CRS	NIRS	VRS
Herbicide tolerant							
Same technology[2]	0.33(0.16)	0.76(0.18)	0.77(0.18)	0.86(0.12)	0.79(0.18)	0.79(0.18)	0.86(0.13)
Productivity	0.99	0.86	0.87	0.84	0.50	0.53	0.56
Overall[3]	0.33(0.16)	0.65(0.19)	0.67(0.19)	0.72(0.18)	0.40(0.32)	0.42(0.33)	0.49(0.34)
Stacked gene							
Same technology[2]	0.43(0.15)	0.80(0.19)	0.82(0.20)	0.87(0.16)	0.81(0.18)	0.83(0.19)	0.88(0.14)
Productivity	0.53	0.95	0.94	0.95	0.63	0.66	0.68
Overall	0.23(0.08)	0.76(0.20)	0.77(0.21)	0.82(0.18)	0.51(0.36)	0.55(0.37)	0.60(0.35)
Conventional							
Same technology[2]	0.36(0.19)	0.86(0.16)	0.88(0.16)	0.90(0.13)	0.77(0.29)	0.79(0.27)	0.82(0.25)
Productivity	0.93	0.77	0.77	0.80	0.41	0.46	0.49
Overall	0.33(0.17)	0.66(0.18)	0.68(0.19)	0.73(0.16)	0.32(0.28)	0.36(0.33)	0.40(0.32)

[1] Standard deviation in brackets.
[2] Using growers with the same technology as the reference base.
[3] Using all growers as the reference base.

Table 3 Abatement cost efficiency scores of herbicide tolerant, stacked gene and conventional cotton production

Performance measure by technology	Abatement cost efficiency				
	Mean	s.d.	Lower quartile	Median	Upper quartile
Herbicide tolerant					
Same technology[1]	0.86	0.13	0.73	0.88	1.00
Productivity	0.60				
Overall[2]	0.52	0.31	0.26	0.38	0.93
Stacked gene					
Same technology[2]	0.88	0.14	0.78	0.94	1.00
Productivity	0.68				
Overall	0.60	0.35	0.27	0.48	1.00
Conventional					
Same technology[2]	0.83	0.24	0.69	1.00	1.00
Productivity	0.57				
Overall	0.47	0.29	0.26	0.32	0.65
All growers	0.54	0.32	1.00	0.39	0.26

[1] Using growers with the same technology as the reference base.
[2] Using all growers as the reference base.

ENDNOTES

[i] Except for McKitrick (1999) who finds that the MAC function may exhibit kinks and jumps.

[ii] Strong disposability refers to the ability to dispose of an unwanted commodity with no private costs. Weak disposability refers to the ability to dispose of an unwanted commodity at a positive private cost.

[iii] Similarly, Rennings (2000) distinguished integrates measures, such as substitution for ecologically harmful inputs, optimization of process components and using an alternative production process, from additive measures that solely focus on emission reduction.

[iv] Farms are frequently X-efficient; output (environmental performance, profit) is less than the ideal maximum for the specific firm. Habitual behaviour based on imperfect information is an important cause of X-efficiency and it can affect production in several ways. Lack of knowledge how to attain the highest profit level for a given combination of inputs, may lead producers to use inputs inefficiently. Producers may also have limited knowledge of the set of alternative production technologies that are available and their economic and environmental characteristics, as well as a lack of information about how their actions affect environmental quality (Ribaudo and Horan, 1999).

[v] The planting date influences insect control, pant growth regulator, and defoliant strategies indirectly. Crop rotation aids in the control of nematodes and diseases. Additionally it can be a significant component of weed management. No-till system can save time, allowing growers to plant cotton closer to the optimum planting dates.

[vi] Two methods are available to measure efficiency. Stochastic frontier analysis (SFA) and data envelopment analysis (DEA). SFA assumes a parametric specification for the production technology, which can confound the efficiency results. Furthermore, SFA makes explicit assumption about the distribution of the efficiency term and concavity in inputs is not generally satisfied when using the common translog specification. The DEA approach avoids a specification of the technology or assumptions about the distribution of the efficiency term to be imposed while meeting curvature conditions (Oude Lansink *et al*., 2002). For other applications of DEA to determine efficiency of polluting inputs see *e.g.*, Tyteca (1997) and Reinhard *et al*. (2000).