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Pollution shadow prices in conventional and organic farming: an application in a Mediterranean context

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Abstract

Organic farming integrates environmental concerns and criteria within farm management practices in order to reduce the environmental impact of agricultural production. In this paper, the shadow price of two of the main indicators of pollution arising from agricultural practices, nitrogen surplus and impact of pesticides, are calculated and compared in a context of Mediterranean climate and cultures. Results show that it is more costly for organic farms to reduce their levels of pollution emission than for conventional farms. This may be due to the fact that the specific regulations on organic farming restrict agricultural practices to a larger degree than current restrictions affecting conventional farming. These results suggest that organic farming might be an adequate answer to part of the environmental problems provoked by conventional farming.

Additional key words: DEA; directional distance; organic regulation.

Resumen

Precios sombra de la contaminación en la agricultura orgánica y convencional: una aplicación en la agricultura mediterránea

La agricultura ecológica integra criterios ambientales en las prácticas de producción agrícola con el objeto de mejorar el impacto de la producción agraria sobre el medio ambiente. En este trabajo se estiman y comparan los precios sombra de dos de los contaminantes más importantes en la producción agraria, el excedente de nitrógeno y la contaminación por pesticidas, en el contexto de la agricultura mediterránea. Los resultados muestran que el coste marginal de reducción de la contaminación es más alto para las explotaciones ecológicas que para las convencionales. Ello estaría indicando que la regulación de agricultura ecológica es de hecho más restrictiva ambientalmente que la de la agricultura convencional. En este sentido los resultados sugieren que la agricultura ecológica podría ser una respuesta adecuada a algunos de los problemas ambientales provocados por la agricultura convencional.

Palabras clave adicionales: agricultura ecológica; DEA; precios sombra de la contaminación.

Introduction

The environmental impact caused by agricultural practices is generating increasing interest and concern in society. The process of intensification of agricultural production initiated decades ago has meant, in addition to a spectacular increase in agricultural productivity, higher environmental impacts brought about by agricultural practices. This intensification has provoked environmental problems such as aquifer pollution, bioaccumulation of toxic residues of agro-chemicals on living tissues and the loss of biodiversity, to name but a few.

In this context, organic farming appears as a production system whose objective is to create integrated and

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Abbreviations used: AWU (annual work units), CPAEN/NNPEK (Consejo de la Producción Agraria Ecológica de Navarra/Nafarroako Nekazal Produkzio Ekologikoaren Kontseilua), DEA (data envelopment analysis), EIQ (environmental impact quotient), FADN (farm accountancy data network), UAA (utilised agricultural area).

sustainable systems from an environmental, economic and social perspective (Lampkin, 1994). The minimisation of the dependence on external inputs is sought, trying at the same time to maximise the resources available in the farm, in the form of closed cycles. With this aim, environmental considerations are integrated within farm management practices in order to preserve soil fertility and its biological activity in the long term, trying to avoid, as far as possible, all environmental impacts arising from the agricultural activity, which may imply, in turn, a sacrifice in output or revenues.

A key point for the implementation of an environmental-technical regulation in a productive sector is the determination of firms' economic costs implied by the compliance. It may be expected that, the more restrictive the regulation, the higher the economic sacrifice firms need to make for that compliance. In this sense, the computation of shadow prices may provide some information about the environmental impacts and the costs of an environmentally friendly production from the field of production economics. Shadow prices measure the marginal sacrifice needed, in terms of revenues or production, to comply with some environmental restriction on a given pollutant, for instance, or the marginal cost of pollution abatement. This information also allows us to compare the impact on diverse productive sectors of different regulatory frameworks. This way, it would seem reasonable to expect higher marginal costs of pollution abatement, or shadow prices, in those scenarios with higher environmental restrictions, that is, higher pollution shadow prices in organic than in conventional farming, given the larger degree of environmental restrictions of organic compared to conventional farming. This is precisely the context in which this research is placed.

The comparison of pollution shadow prices in conventional and organic farming, in addition, may allow us to analyse the role played by farms engaged in organic farming programmes towards a better environmental quality.

Comparing conventional and organic farming, though, is not a straightforward task, as there are a number of difficulties associated. The first problem arises from the very concept of organic farming and its holistic approach that, unlike conventional farming, places emphasis on considering the farm as a system where all the elements interact with each other. This fact makes it difficult to establish comparisons, because «we are dealing with different systems, not modifications to individual practices» (Lampkin, 1994, p. 31). According to this author, the widespread practice of comparing both methods of production, conventional and organic, based only on some selected variables would be inadequate because it would neglect this consideration of organic systems as a whole. This view is also shared by Roberts and Swinton (1996), who consider that the validity of the comparisons relies upon the closeness of technologies. Another problem pointed out by Cacek and Langner (1986) and by Roberts and Swinton (1996) is the fact that organic farming is characterised by a high diversity of crops, as opposed to conventional farming, that tends to crop specialisation.

In addition to the above, a fundamental limitation encountered when organic and conventional farming systems are compared, although not exclusive of this kind of analysis, is the lack of consideration of the environmental impacts of each system, the environmental external costs. That is, economic comparisons are carried out, but the distinct effects on the environment of each system of production are not taken into account. Faeth *et al*. (1991) indicate, as cited in Lee (1992, p. 83): «... this failure to account explicitly for environmental damages when analysing low-input systems has seriously distorted the economic comparisons of low-input and conventional agricultural production systems.»

This idea is also mentioned by Roberts and Swinton (1996, p. 10) in the following terms: «Typically these systems are neither more profitable nor higher yielding than the systems they replace. However, they often result in less contamination of ground and surface waters, less pesticide residue on the marketed product, or better soil quality. Having been designed to attain these environmental objectives, these systems cannot be evaluated fairly on productivity criteria alone.»

Taking the above into account, it has to be pointed out that, so far, the majority of contributions to the literature on this «comparative» approach have been carried out from a rather partial approach. In other words, these works do not integrate those features characterising conventional and organic farming systems globally, but rather select only a given field from which comparisons are made.

With this respect, most studies comparing conventional and organic farming focus on two aspects: environmental impact and economic performance, both studied from several points of view. Thus, the differences in the environmental impacts arising from both systems are analysed (Stolze *et al*., 2000), as well as differences in yields (Offerman and Nieberg, 2000;

Lotter, 2003), costs, profits and price differentials (Offerman and Nieberg, 2000).

Likewise, in the field of production economics this kind of analysis has been traditionally carried out from this somewhat incomplete point of view, that is, without considering these features that characterise organic farming, undoubtedly influencing its performance. This fact is specifically acknowledged by Oude-Lansink *et al*. (2002) and Sipiläinen and Oude-Lansink (2005), who recognise that no consideration of the environmental impacts of any kind has been taken into account when carrying out their respective studies on the efficiency of conventional and organic farming systems.

In this matter, this work tries to overcome these limitations and integrates economic, as well as environmental variables in the analysis. The objective of the present paper is the computation of the shadow price of pollution arising both from conventional and organic farming. This is done, not only to find out the marginal cost of pollution abatement in each production system, but also to be able to compare these shadow prices in order to analyse to what extent the regulation of organic farming contributes towards an improvement in environmental quality. In this sense, the computation of the shadow price of two of the main indicators of contamination arising from agricultural practices, namely, nitrogen excess and pesticide impact, may serve as a guide for prioritization of agrienvironmental subsidies, for example, organic over conventional farming, or otherwise. In addition, this information may also advise authorities in the process of adjustment of the regulations, with specific reference to fertilization and pesticide management practices, in this particular case.

To the best of our knowledge, this work provides the first attempt to apply this particular framework in a Mediterranean context. So far, other comparisons have been made between conventional and organic farming and Mediterranean cultures, such as Greek olive-growing (Tzouvelekas *et al*., 2001a) and cotton farms (Tzouvelekas *et al*., 2001b). These works, though, do not calculate pollution shadow prices and are restricted to the computation of efficiency indexes with no consideration of environmental impacts, as in the aforementioned works by Oude-Lansink *et al*. (2002) and Sipiläinen and Oude-Lansink (2005). On the other hand, the only available piece of research facing specifically this issue (Zhengfei *et al*., 2005), is an application to the efficiency of Dutch agriculture hardly comparable to the Mediterranean context.

With this objective, a non-parametric analysis is carried out, based on the concept of directional output distance function. Shadow prices are calculated as the ratios of the dual variables associated with each restriction in the linear program, following Ball *et al*. (1994) and Oude-Lansink and Silva (2004), among others. As described above, attention is focused on two particular indicators of pollution arising from agriculture such as nitrogen excess and the impact of pesticides.

Methodology

Data envelopment analysis (DEA) model for the computation of shadow prices

The fact that the production of goods and services has negative effects on the environment has been reflected in production economics by the hypothesis of weak disposability (Shephard, 1970). It is considered that production process has outputs of two types: one, desirable, goods and services, and another one, undesirable, pollution or the negative effect on the environment brought about by the process. Desirable output is a good viewed as strongly disposable, in other words, a decrease in its amount has no cost. On the other hand, the reduction in pollution levels has a cost, that is, it is weakly disposable.

In this work, we try to examine, precisely, what is the marginal cost of the reduction of pesticide and fertiliser pollution in conventional and organic farming. In other words, how much desirable output has to be given up by efficient farms in each sector in order to reduce pollution at the margin.

With this objective, the directional distance function will be used, which is defined next. Let us consider an input vector $x=\left(x_1,\ldots,x_n\right)\in\Re^n_+$, a desirable output vector $y=\left(y_1,\ldots,y_m\right)\in\Re^m_+$ and an undesirable output vector $b=\left(b_1,\ldots,b_r\right)\in\Re^r_+$. Production technology may be represented by an output correspondence $x\to P\left(x\right)\subseteqq\Re^{m,r}_{++}$, where $P(x)$ is the output set that can be obtained from a given input vector. This correspodence satisfies certain axioms (Shephard, 1970). For the case that y is disposable and b is not, it holds that if $(y,b)\in P(x),(\theta\, y,\theta\, b)\in P(x)\ \forall 0\leq\theta\leq 1$.

Production set may also be defined by the directional distance function, which is defined as:

$$\vec{D}_O\left(x, y, b; g_y, g_b\right) = = \max\left\{ \beta : \left(y + \beta g_y,\ b - \beta g_b\right) \in P(x)\right\} \quad [1]$$

where (g_y, g_b) is the directional vector. This function indicates the maximum expansion and contraction in good and bad output, respectively, which is feasible given technology $P(x)$.

Following Ball *et al.* (1994) and according to the duality between the directional distance function and the revenue function (Färe *et al.*, 2004a), the following equivalence may be expressed, by which the shadow price of the undesirable outputs is computed

$$\frac{q_r}{p_m} = \frac{\partial \vec{D}_O\left(x, y, b; g\right) / \partial b_r}{\partial \vec{D}_O\left(x, y, b; g\right) / \partial y_m} \quad [2]$$

where $\partial \vec{D}_O\left(x, y, b; g\right) / \partial b_r$ and $\partial \vec{D}_O\left(x, y, b; g\right) / \partial y_m$ are the dual variables associated with each restriction in the following linear program (3) (Ball *et al.*, 1994; Lee *et al.*, 2002; Shaik *et al.*, 2002; Oude-Lansink and Silva, 2004). These dual variables give a measure of the effect on the distance (or the efficiency) of a change on these constraints[1].

As commented earlier, DEA methodology[2] will be used in the computation of pollution shadow prices. In this particular empirical application, these dual variables are obtained from the computation of the following linear program (primal and dual formulations are specified in the Appendix):

$$\begin{aligned} &\vec{D}_{strong}\left(x_k, y_k, b_k; y_k, b_k\right) = \max \beta \\ &\text{subject to} \\ &\sum_k \lambda_k y_{mk} \geq (1+\beta)\, y_{mk} \qquad m = 1, \ldots, M \\ &\sum_k \lambda_k b_{rk} \leq (1-\beta)\, b_{rk} \qquad r = 1, \ldots, R \\ &\sum_k \lambda_k x_{nk} \leq x_{nk} \qquad n = 1, \ldots, N \\ &\lambda_k \geq 0 \qquad k = 1, \ldots, K \end{aligned} \quad [3]$$

where there is a sample of $k = 1, \ldots, K$ farms, $m = 1, \ldots, M$ desirable outputs, $n = 1, \ldots, N$ inputs and $r = 1, \ldots, R$ undesirable outputs; λ_k are the intensity variables or weights and $(y_k, -b_k)$ is the directional vector.

Two essential methodological aspects in the computation of shadow prices with the directional distance function are: how to specify the weak disposability restriction for the undesirable outputs and which directional vector to choose. As shown in the linear program [3] above, in this particular case undesirable outputs have the same restriction as inputs (Hailu and Veeman, 2001) and the directional vector used is $(y_k, -b_k)$. Next, we will comment on these two decisions.

Regarding the definition of the production set and the frontier of efficiency, an important debate exists on how to specify the weak disposability axiom by Shepard (1970) in the definition of the output set and the distance function in DEA. This debate is of particular relevance when we have real production sets with «super-polluting» units. We call «super-polluting» units those units that, for a given input level, have more pollution emissions than the most polluting efficient unit.

In Figure 1 the production set is depicted with a good output, y, and a bad output, b; for a given input level x, a, b and c are extreme units of the actual production set, b is the efficient unit with the highest emission level, c is an extreme «super-polluting» unit and unit i represents a non extreme «super-polluting» unit. Oabcd represents the envelope of the production set for a convex technology when an equality restriction for undesirable outputs (Färe *et al.*, 1989) is used in DEA[3]. A projection of unit i towards the envelope

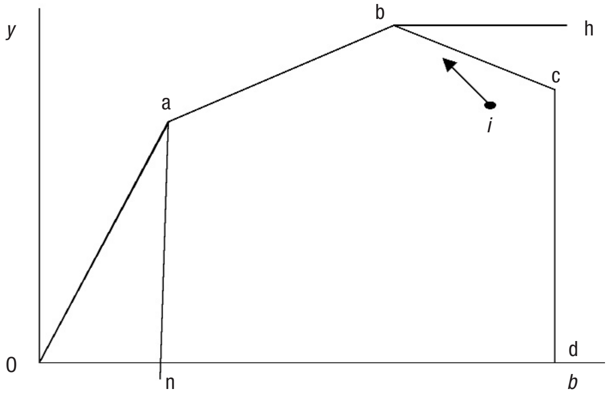

Figure 1. Production set desirable output y – undesirable output b.

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[1] For a more detailed explanation on the basis of this approach, see Shephard (1970, Section 11.4).

[2] The software package used is GAMS 21.7 (General Modeling Algebraic System).

[3] This is a way of specifying the weak disposability axiom of Shephard (1970) in DEA. It means that if $(y,b) \in P(x)$, $(y',b) \in P(x)$ $\forall y' \leq y$.

of the production set, using the directional distance indicated by the vector in the diagram, would place that unit on section b-c of the envelope. The slope of b-c determines the computed shadow price of pollution for unit *i*. On that section, substitution relationship between good and bad output is negative which, would give us the (positive) shadow value of pollution for that unit. In other words, pollution reduction would imply an increase in desirable output.

If it is considered that the shadow value of pollution indicates the marginal social cost of its reduction, measured in terms of good output, the result above would be an absurd. This would indicate that there are efficient firms that may reduce pollution by increasing production. The problem is that the «super-polluting» units on the envelopment of the production set to the right of unit b are not efficient.

The shadow value of pollution that will be used in this research tries to express the social cost of pollution reduction as the opportunity cost of its reduction in terms of good output for the efficient units. We are not concerned by the social costs brought about by inefficiency. The problem is that, depending on how the weak disposability restriction is specified in DEA or on which directional vector is chosen, it may happen that those «super-polluting» units on the envelope of the production set are classified as efficient for purposes of shadow price computation.

In the literature, several methodologies have been suggested in order to correct for this problem. For instance, Picazo-Tadeo and Prior (2009) propose a two stage process in the context of efficiency measures. Färe *et al*. (2006) give a specific definition of directional weak disposability which, in the last instance, means treating the bad output as an input. Without getting into deeper arguments on this debate, the use of a $\leq$ restriction[4] for undesirable outputs in the specification of the distance function allows attributing null value to the shadow price of those super-polluting units that, after having good and bad output increased and decreased, respectively, according to the distance function used in this work could subsequently increase efficiency by reducing pollution. This implies a change in the envelope, that now would be segment nabh, and the projection of unit *i* towards segment b-h of the new envelope. We have adopted this approach.

This choice of the directional vector is of particular importance in the current context of any environmental policy. It is usually considered to be up to the researcher and it depends on the objective of the specific application put in place. However, in a context where undesirable outputs or by-products are to be taken into account, the directional vector more commonly used is the own observation, $(g_y, g_b) = (y, -b)$, that measures the maximum equiproportionate increase and decrease in goods and bads, respectively. Besides, the choice of the own observation makes the determination of the directional vector straightforward. This is the vector used in this empirical application.

Another vector used in the literature, although to a much lesser extent, is the vector $(g_y, g_b) = (1, -1)$, that assigns the same value to each unit of expansion and contraction of the desirable and undesirable outputs respectively (Färe *et al*., 2005; Huhtala and Marklund, 2005). This vector may be useful for comparative purposes among firms (Chung, 1996) and because, assuming allocative efficiency and a common directional vector for all firms, the sum of firms' efficiencies corresponds to the efficiency of the industry. Additionally, it is consistent with a requirement for reduction in undesirable outputs (Färe *et al*., 2005). Nevertheless, the choice of a fixed vector that equally credits increases in good outputs and reductions in bad outputs should be further justified (Chung, 1996). The last option[5] cited in the literature is the use of the price vector as directional vector (Chung, 1996). This option, however, would require the derivation of the shadow prices of the bads, given that their prices are not normally observable.

Data collection and variables

The dataset used for the present empirical application corresponds to a sample of 86 farms from the region of Navarre (Northern Spain), for the year 2001. This sample is further divided into two sub-samples. The first sub-sample corresponds to 54 conventional farms, whose data (FADN) were provided by the Technical Secretary of the Department of Rural Development and Environment of Navarre. According to the European classification by types of farming (Commission

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[4] It means that if $(y,b) \in P(x)$, $(y',b') \in P(x)\ \forall y' \leq y,\ b' \geq b$.

[5] Lee *et al*. (2002) calculate the directional vector by utilizing the annual abatement schedules of pollutants and the production plans of good output as proxy variables for bads and goods, respectively.

Decision 85/377/EEC), these farms may be classified either as Type 311, *Specialist quality wine*, or as Type 603, *Field crops and vineyards combined*.

The second sub-sample consists of 32 organic farms certified by the Council of Organic Agricultural Production of Navarre (CPAEN/NNPEK, Consejo de la Producción Agraria Ecológica de Navarra/Nafarroako Nekazal Produkzio Ekologikoaren Kontseilua), which fall also under the two previous farming types, that is, Type 311 and Type 603. Specifically, 72% of farms in the organic sample obtain more that 50% of their revenue from organic farming and 50% of the sample obtain 100% of their revenues from organic farming, in other words, they are *pure* organic farms.

Four inputs (land, labour, capital and fertilisers and pesticides), one desirable output (total revenues) and two undesirable outputs (nitrogen excess and impact of pesticide use) are considered in the study. Specifically, land is measured in hectares of utilised agricultural area (UAA); total labour is measured in annual work units (AWU); capital is measured in euros, corresponding to depreciation and hire of machinery and buildings; and the total amount of fertilisers and pesticides employed in the farm, in euros, that account for expenses in fertilisers and pesticides. A unique, aggregated[6] output has been considered in the analysis because, in spite of the fact that vineyard cultivation is farms' main orientation, the great majority are multiproduct farms, and culture compositions vary from farm to farm. This approximates the impact of endogenous quality[7], in the form of the organic label. Certain characteristics exist that differentiate both categories of products and these characteristics are reflected in the price paid for organic produce, higher than conventional price. Accordingly, the desirable or good output variable to be used, is total revenues in euros (Tzouvelekas *et al*., 2001a,b; Huhtala and Marklund, 2005; Larsen and Foster, 2005; Madau, 2005; Zhengfei *et al*., 2005). The differences in quality between conventional and organic products, as represented by the higher price paid for organic products are, therefore, introduced in the output variable.

Regarding the undesirable outputs, nitrogen excess (kg) is calculated following the method of soil surface nitrogen balance by the OECD (2001). This method calculates the difference, based on the nitrogen cycle, between the nitrogen inputs entering the soil and the nitrogen outputs leaving the soil. Data on fertilisation strategies, such as products and quantities used, as well as on harvested crops, were gathered during the interview with organic farmers in order to allow for the calculation of the balance of nitrogen. In the case of conventional farmers, the available data are monetary expenses in fertilisers only. In order to determine the quantities of nitrogen applied, a fertiliser price index was elaborated, weighting according to fertilisation strategies[8]. Finally, OECD coefficients for nitrogen extraction by crops, biological nitrogen fixation and atmospheric deposition were used.

The undesirable output that accounts for the environmental impact of pesticides was calculated following the method by Kovach *et al*. (1992). This method is used to calculate the impact on the environment of the pesticides most commonly used in the treatment of fruits and vegetables. The value obtained, the environmental impact quotient (EIQ), may be used to compare the environmental impact of different management techniques or strategies. As in the case of nitrogen balance, data on pesticide management strategies, such as products used and quantities applied, were obtained from the interview with organic farmers. The data of conventional farms were obtained using the amount of pesticide purchase and a price index, applying the methodology explained above to the case of pesticides.

Results

Description of the sample

Summary statistics of the data are presented in Table 1. As can be observed, there are no great differences between the size and structure of the two subsamples, conventional and organic.

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[6] As acknowledged by Tauer (2001), Färe *et al*. (2004b) and Barnum and Gleason (2006), among others, aggregating outputs (and inputs) means that technical efficiency measures are biased due to allocative inefficiency. The dimension of this bias will probably vary among firms, which implies that the rankings of firms may also vary at diverse aggregation levels (Färe *et al*., 2004b).

[7] The organic label provides a differentiation of endogenous quality in which the price realised may be viewed as function of the characteristics of the product, which result from a number of management practices, voluntarily adopted by the producers (Kristofersson and Rickertsen, 2004). Exogenous quality, on the other hand, is determined by other factors that are beyond producer's control, such as origin or location (Daraio and Simar, 2005).

[8] These fertilisation strategies are proposed for the different locations in the sample by technicians of the ITG-Agrícola (Technical Institute of Agricultural Management).

Table 1. Descriptive statistics of the data set (average values, standard deviations between parentheses)

	Land (ha)	Labour (AWU)[1]	Capital (€)	Fert/pest (€)	Output (€)	Nitrogen (kg)	EIQ (EIQ units)[2]
Whole sample	54.27	1.61	9,008	6,562	63,081	5,038	1,887
	(49.5)	(0.75)	(6,791)	(5,958)	(46,749)	(5,575)	(829)
Conventional	58.25	1.52	9,246	6,218	53,351	5,084	1,490
	(52.4)	(0.55)	(6,724)	(5,574)	(35,142)	(5,076)	(127)
Organic	47.54	1.76	8,606	7,141	79,501	4,960	2,557
	(44.2)	(1.00)	(6,993)	(6,607)	(58,633)	(6,416)	(1,059)

[1] AWU: annual work units. [2] EIQ: environmental impact quotient.

Tables 2 and 3 show the ratios of inputs and the amount of nitrogen and EIQ per euro of output. As figures show, conventional farms use more inputs per euro of output. Also, organic farms show lower levels of nitrogen surplus per euro of output and, on the contrary, higher EIQ levels than conventional farms.

With respect to these data, it has to be pointed out that organic farming fertilisation is manure-based, as opposed to conventional farming, in which chemical synthesis fertilisers, easier to manage and apply, are also allowed. This manure-based fertilisation is quite a labour-intensive activity, which certainly affects its demand. This, among other factors, makes the build-up and surplus of nitrogen less likely to occur in organic farm soils and results in lower nitrogen surpluses. On the other hand, the higher EIQ levels in organic farms may be explained by the heavy reliance on sulphur and copper-based products for the treatment of vineyards. Due to the lengthy persistence on soils of these products and the potential damage to some beneficial insects, they are given high EIQ values[9], higher in some cases than EIQs of conventional pesticides. In fact, copper use has been restricted in the European Union and is not allowed in certain countries, its total phase-out being foreseeable in the future. This figure may seem counterintuitive at first, but it has to be taken into account that the EIQ field use rating depends highly on the rate of application, made up by both the dose and the frequency of application. Therefore, high rates of application of sulphur and copper-based products in organic farms lead to high EIQ field use ratings. On the other hand, low doses of other conventional pesticides (prompted by usually higher prices), that may get as high individual EIQs, lead to lower EIQ field use ratings for conventional farms.

Table 2. Inputs per euro of output (average values)

	Land/O	Labour/O	Capital/O	F&P/O[1]
Whole sample	$8.6 \cdot 10^{-4}$	$2.5 \cdot 10^{-5}$	0.143	0.104
Conventional	$1.1 \cdot 10^{-3}$	$2.8 \cdot 10^{-5}$	0.173	0.116
Organic	$6 \cdot 10^{-4}$	$2.2 \cdot 10^{-5}$	0.108	0.09

[1] F&P: fertiliser and pesticide expenses.

Shadow prices estimates

In this section, the results for the shadow prices of nitrogen and pesticides, obtained for a model that treats these environmentally detrimental variables as inputs will be analysed. In this case, since desirable output is total revenues or production value, the shadow price indicates the revenue that has to be given up in order to reduce pollution by one unit.

These results may be analysed from two points of view. On the one hand, the use of the non-parametric methods of efficiency measurement gives a measure of the shadow price on the projection of each unit on the frontier. Therefore, these shadow prices represent the marginal rate of transformation between the good output and the bad (treated as an input), regardless of where the unit is projected on the frontier, which is

Table 3. Nitrogen and environmental impact quotient (EIQ) per euro of output (average values)

	Nit/Output	EIQ/Output
Whole sample	0.080	0.030
Conventional	0.095	0.028
Organic	0.062	0.032

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[9] For a complete list of EIQ values and a detailed description of the methodology go to: http://www.nysipm.cornell.edu/publications/eiq/

determined by the orientation chosen in the model, vector $(y_k, -b_k)$, the own observation in this case.

On the other hand, the significance and implications for the society of these shadow prices, *i.e.,* the opportunity cost of pollution in terms of farm revenue may be analysed. With this objective in mind, it is fundamentally the farms which really show an opportunity cost when reducing pollution that we are interested in, because it is precisely the per output emission levels of these units which should be considered when trying to set really restrictive environmental standards

In true, it is crucial to differentiate the units with a positive opportunity cost of pollution reduction from those whose cost is zero. The units showing a zero opportunity cost are those that, having increased and decreased good and bad output, respectively, according to the distance function used in this work could subsequently increase efficiency by reducing pollution. Therefore, the social opportunity cost of a marginal improvement in the environmental performance of these units is null.

Generally speaking, all units with zero shadow price are super-polluting units, but the opposite is not true. This depends to a great extent on the directional vector used. In this particular case, as mentioned above, we considered it important that the direction of projection of each unit towards the frontier were defined by its actual combination of good and bad outputs.

Table 4 displays the average results for conventional and organic samples. We present two averages for the shadow price: that of the whole sample (including units with null shadow price) and that of units with positive shadow price (social opportunity cost) only, according to the description above.

The large difference between these two average measures of the shadow prices opportunity cost, though, including units with opportunity cost zero and otherwise, for the two contaminants and for the two agricultures is important for the following reason: It indicates that the implementation of an environmental policy more restrictive than the current one would not represent a great sacrifice for society as a whole. For example, if an environmental technical standard set a per output emission level at the level of the marginal unit with positive pollution shadow costs, this could be attained with no sacrifice by society, provided that some «superpolluting» units increased further their environmental efficiency.

Table 4. Average shadow prices (in euros). Standard deviations between parentheses

	Shadow price			
	All units		Social cost	
	Nitrogen	Pesticides	Nitrogen	Pesticides
Conventional	9.3 (10.8)	33.7 (37.1)	14 (10.5)	38.8 (37.3)
Organic	82.3 (430)	48.9 (38.3)	188 (649)	58 (34.7)

As opposed to considering a unique sample as the subject of study, this analysis has been carried out separately for the conventional and organic farm subsamples. Since the shadow price gives an indication of the slope of the transformation curve, we ignore, in case a unique sample is analysed, whether the shadow price is reflecting the opportunity cost of pollution reduction between the two regulations. And this, in turn, does not allow measuring the restriction imposed by each regulation independently, that is, the good output that has to be sacrificed in order to comply with it.

Comparing the aggregated results for conventional and organic farming, there are three points worth emphasising. First, the weight of units with zero or positive shadow price is much higher for nitrogen than pesticides, both in conventional and organic farms. As mentioned previously, this may reflect a more restrictive regulation for pesticides —through product residues— than that of nitrogen. This has somehow generated an intrinsic culture in the sector, reflected by the observance of safety periods in pesticide application, for instance.

Second, nitrogen shadow prices are substantially higher in organic than in conventional farms, which indicates that the marginal cost of nitrogen pollution is higher, in terms of farm revenue, for organic than for conventional farms. This implies that the efficient frontier of organic regulation, on which organic farms are projected, is steeper than the efficient frontier of conventional farming. This indicates that organic regulations are more restrictive concerning this aspect.

This result seems consistent with a view of the regulation of organic farming as a regulation targeted at the environmental quality of the inputs. In fact, pollution arising from organic fertilisation, *i.e.,* from animal manure application, is lower than that coming from conventional fertilisation operations, *i.e.,* from chemical synthesis products. Lower nitrogen surpluses of organic farms in the sample give evidence of this.

However, fertilization cost is higher in organic agriculture because animal manure application is quite a labour-intensive activity, and this might reduce demand of this fertilize in organic farms. The conjunction of these two factors, and not only the environmental quality of manure, might be the cause of the higher shadow price of nitrogen of organic farms.

Likewise, the shadow price of pesticides is also higher in organic than conventional farms. This result may seem counterintuitive at first, especially if it is taken into account the higher EIQ levels by organic farms, as shown in Tables 1 and 3. However, it may be due to the fact that organic farmers rely on cultural practices more than conventional farmers do, as reflected by the lower levels of fertiliser and pesticide expense per unit of output. For instance, more non-chemical methods of weed control are put in place, such as mechanical manual cultivation, mulching and cover crops, to prevent weeds from germinating and growing. Farm management techniques for disease and pest infestation management, other than the resource to chemical products, also contribute to explaining this higher shadow price. In addition, organic prices and, therefore, revenues, are higher, which implies more revenue forgone for pesticide reduction.

These shadow prices also give us an idea about the slope of the respective facets of the efficient frontiers. It is evident that the slope nitrogen-desirable output is much steeper in the case of organic farms, because the shadow price is higher. For pesticides, the slope is steeper too, although to a lesser degree, as reflected by the shadow price values in Table 4.

Finally, there is quite a noticeable higher dispersion on nitrogen pollution shadow price in organic farms, as indicated by the standard deviation in Table 4. This result may be due to the fact that the output-nitrogen excess transformation curve has a great slope variation, and also to the fact that the dispersion of nitrogen excess per output is very high. The dispersion of nitrogen excess per output is higher in organic than in conventional farms, which may be explained by the lack of standardisation on organic agriculture production practices. This is in essence true as regards the utilisation of manure as fertiliser, since farmers do not possess a priori knowledge on the nutrient richness of the manure they use[10]. However, this fact seems insufficient to justify these differences in the dispersion of nitrogen excess shadow price values[11]. Therefore, to our understanding, the higher dispersion on nitrogen excess shadow price in the organic agriculture is due to: 1) the great increase in marginal emission abatement costs as these emissions decrease, and 2) the higher dispersion in nitrogen excess levels per output unit in organic farming.

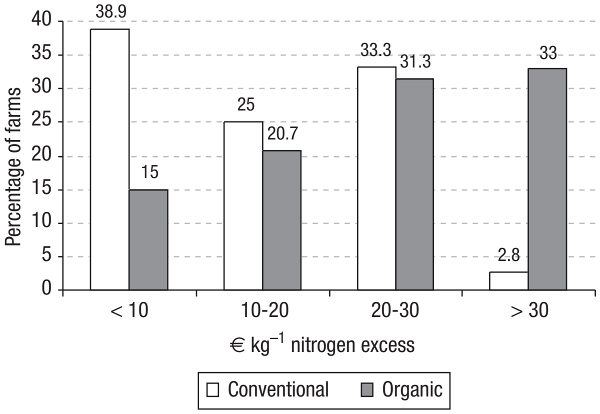

Figure 2. Distribution of farms by nitrogen shadow price.

To analyse more accurately the transformation curve and the performance of the units in the two sectors, Figures 2 and 3 present the shadow prices distribution by ranges.

Regarding the shadow price of nitrogen, the divergence between the percentage of conventional and organic farms falling into the first range, less than €10

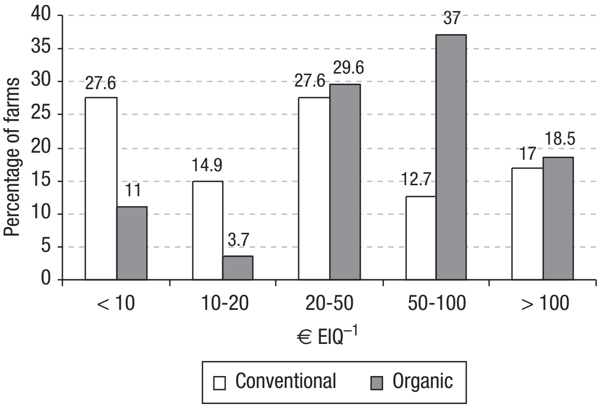

Figure 3. Distribution of farms by pesticide shadow price.

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[10] In fact, a new program of education and research is being implemented in the region with the objective of teaching farmers various simple procedures for approximating manure nutrient richness.

[11] The variation coefficient of nitrogen excess per output is 0.74 for conventional farms and 1.27 for organic farms. The variation coefficient of the shadow price varies between 1.16 (conventional farms) and 5.24 (organic farms).

kg^{-1} of nitrogen excess, is quite noticeable, 38.9% of conventional farms and 15% of organic farms. In the other range extreme, more than €30 kg^{-1} of nitrogen excess, only 2.8% of conventional farms are found, as opposed to 33% of organic farms. Also, it is shown that more than 60% of organic farms show a shadow price value higher than €20 kg^{-1} of nitrogen. In the case of conventional farms, this values goes down to 36%.

With respect to the shadow price of pesticides, the lower range extreme shows higher differences than in the case of nitrogen: 27.6% compared to 11% of conventional and organic farms, respectively, show shadow prices lower that €10 EIQ^{-1}. This divergence, though, becomes rather similar in the other range extreme, values higher that €100 EIQ^{-1}, with 17% and 18.5% of conventional and organic farms, respectively; 55.5% of organic farms show a value higher than €20 EIQ^{-1}, but this value goes down to 30% in the case of conventional farms.

Discussion

Some prudence is needed if one wants to compare these results with other shadow prices shown in the literature. In the first place, shadow prices are expressed in different units and the possibility of establishing meaningful comparisons is, therefore, limited. For instance, the majority of literature references express the shadow price as euros per additional euro spent on either nitrogen or pesticides, whereas we express the shadow price as euros per additional kg of nitrogen surplus or additional EIQ unit. In addition, Färe *et al.* (2006) express the shadow price of nitrogen leaching and runoff as index of crop revenue per index of leaching.

In the second place, apart from this divergence on what is measured and how it is expressed, there are also differences regarding the methodologies employed, that vary from the calculation of the shadow price based on the dual values obtained from the restrictions of a non-parametric DEA model (Piot-Lepetit and Vermersch, 1998; Oude-Lansink and Silva, 2004) to calculations based on the duality between the output (input) distance function and the revenue (cost) function by parametric estimations (Shaik *et al.*, 2002; Färe *et al.*, 2006). Moreover, the differentiated treatment given to the environmentally detrimental variables, which can be treated as inputs or undesirable outputs and, also, the consideration of the strong/weak disposability hypothesis, contribute to a rather constrained comparability of results.

Taking the above into account, the shadow price of nitrogen pollution obtained in this application may be comparable, to a certain extent, to that by Shaik *et al.* (2002), in that both are expressed in terms of nitrogen excess. Our values, though, are much higher, which may be due to the fact that we deal with dry-farming conditions in a Mediterranean context, which make nitrogen built-up much lower.

Zhengfei *et al.* (2005) obtain much lower values (expressed as additional euro spent on fertilisers and pesticides) than ours. This may be again due to the differences in climatic conditions and cultures, and the fact that Dutch agriculture is highly intensive, compared to this case. Another interesting feature of this reference is that the shadow price of both fertilisers and pesticides is higher in organic than in conventional farms, a result also arising from this analysis. Dabbert and Piorr (1998) obtain that nitrogen shadow prices are up to 6 to 7 times higher in organic farming. This amounts to up to 9-14 times in this case. Again, dry-farming conditions may help to explain this divergence in shadow price values.

Färe *et al.* (2006) express the shadow price and the relationship between pollution costs and revenues, for those units located on the frontier in US states agriculture. The relationship between pollution costs and revenues varies between 5 and 15%, which is considered a coherent result with respect to other measures of the cost of pollution in agriculture. If we measure the relationship between nitrogen pollutions costs with respect to output for the efficient units, these amount to 20% and 10% for conventional and organic farms, respectively. The pesticide pollution costs are higher in both samples, organic and conventional. Again, these results differ from those by Färe *et al.* (2006) but they seem reasonable, given that, as mentioned above, this is a dry-farming sample, where much less nitrogen fertiliser and pesticides are used, and the opportunity costs of its reduction are higher.

One important feature of the present empirical application, as underlined above at various points in this section, which perhaps contributes towards the better understanding of the results is the fact that it has been carried out for dry-farming conditions and a mild Mediterranean climate, according to Papadakis Agroclimatic classification (Gobierno de Navarra, 2001). This implies that average nitrogen surpluses per farm and, therefore, per hectare are very low compared to those arising from other conditions, such as irrigated agriculture and more humid climates (Oude-Lansink and Carpentier, 2001; Oude-Lansink and Silva, 2004) or dairy farming (Hadley, 1998). This, in turn, may explain the high nitrogen shadow price values, mainly for organic farms, whose nitrogen balances are even lower. In addition, the total nitrogen surplus is used in the calculation of the shadow price, which does not allow establishing a further distinction among the possible nitrogen pollution routes, such as leaching and runoff, as done by Färe *et al*. (2006). Finally, regarding pesticides, the shadow price has been calculated for the potential environmental impact, as expressed by the EIQ. This gives an idea of how costly may be impact reduction, and not pesticide expense reduction.

As conclusion, in this article we try to give an answer to the economic policy implications of a voluntary technical-environmental program, such as organic farming, when looked at from the production side. These would be the following:

First, is organic farming really environmentally restrictive? That is, does it imply a higher economic sacrifice? The comparison of shadow prices of organic and conventional farms partly responds to this question. The shadow price of nitrogen excess is higher for organic than for conventional farms. This result is also reflected by Dabbert and Piorr (1998), as cited by Kratochvil (2002). Likewise, the shadow price of pesticide impact is higher in the case of organic farms. These results could indicate that, as expected, the amount of revenue that needs to be given up in order to abate one more unit of pollution in each farm, or how much would farmers be willing to pay for increasing pollution by one unit, is higher for organic farmers. Therefore, specific regulations on organic farming restrict agricultural practices to a larger degree than current restrictions affecting conventional farming.

Nevertheless, shadow price differences between organic and conventional farming are smaller for pesticide than for nitrogen pollution. And this is not only explained by the regulation.

Organic farming fertilisation is manure-based (slowly transformed into soluble forms available to plants), as opposed to conventional farming, in which chemical synthesis fertilisers, easier to manage and apply, are also allowed. However, when it comes to explaining the difference between shadow values between the two agricultures, the labour-intensive character of manure use could be also a reason for the low emission levels and high shadow price values. This intensity in labour use might restrict manure use.

As regards to pesticide impact, the higher reliance of organic farmers on cultural management practices, such as mechanical cultivation, mulching and pruning, that reduce the chance of disease (Rombough, 2002), rather than the regular application of pesticides may help to explain the higher shadow price. Nevertheless, as mentioned before, shadow price differences are smaller. This is due, in part, to similar pesticide application systems. And also because an important culture of pesticide use control exists in conventional farming, engendered by existing regulations and by the notable work of public technical extension and assistance services in the region.

Second, there is a question related to the first one: Is it necessary to subsidize organic farming? It could be so, due to the higher shadow costs of pollution of organic compared to conventional farms. This fact shows the environmental superiority of organic standards and could be also a justification to the agri-environmental subsidies to organic farming

Third, could organic regulations be made more restrictive? Yes, because there are many farms with null shadow prices. The great proportion of farms showing null shadow price, both in conventional and organic farming, shows that neither organic nor conventional regulations are very environmentally restrictive. With the distance function used in this work, the units with null shadow price are those that, after having increased efficiency augmenting and reducing proportionally production and pollution, could subsequently reduce emissions for positioning themselves at the per output emission level of the most polluting efficient unit. That is, they may, in theory, reduce their emission levels increasing their environmental efficiency. From the point of view of the regulation, this means that it could be feasible to restrict emissions to certain levels at a null social cost, only by the increase in environmental efficiency of specific farms.

Organic farming regulation is primarily targeted to input environmental quality and it does not a priori determine quantities of neither emissions nor polluting inputs. Then, these results show that there is a lot of room for introducing some restrictions on polluting input quantities, not only qualities, without further output sacrifice.

Four, is there any room for a technological-environmental improvement of organic production farming?

It seems so, since the very dispersion of organic shadow prices gives an indication on that respect.

In fact, relating to the implementation of the organic standard, a crucial aspect in the adoption of new technologies are the learning by doing and learning by using processes. In agriculture, public services of technical extension facilitate both the realisation of these processes and the diffusion of new knowledge throughout the sector. The great dispersion of organic shadow prices is very typical of new technologies, where production processes are not standardised. In line with this, it is also important to highlight the need of more resources for research programmes targeted at the investigation of the different aspects of organic agriculture, which is clearly scarce. Particularly, we identify as crucial the research on the different products for plant protection allowed in the EU organic regulations. In principle, these products are more environmentally friendly than products not allowed. But it might happen that certain market conditions, prompting their use, led to unintended consequences as regards the environmental impact of these products. Scientific research in the subject is, then, essential in order to clarify these aspects and help both farmers and policy makers to make decisions that contribute towards an improved environmental quality, which may be considered, in the last instance, the ultimate aim of organic farming.

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References

BALL V.E., LOVELL C.A.K., NEHRING R.F., SOMWARU A., 1994. Incorporating undesirable outputs into models of production. Cahiers d'Économie et Sociologie Rurales 31, 60-74.

BARNUM D.T., GLEASON J.M., 2006. Measuring efficiency in allocating inputs among outputs with DEA. Appl Econ Lett 13, 333-336.

CACEK T., LANGNER L.L., 1986. The economic implications of organic farming. Am J Altern Agric 1, 25-29.

CHUNG Y., 1996. Directional distance functions and undesirable outputs. PhD dissertation, Dept Economics, Southern Illinois Univ at Carbondale, USA. 118 pp.

DABBERT S., PIORR A., 1998. Ökologischer Landbau. In: Handbuch zum Gewässerschutz in der Landwirtschaft, 2. Auflage (Frede H.G., Dabbert S., eds). Ecomed Verlagsgesellschaft, Landsberg. pp. 280-296. [In German].

DARAIO C., SIMAR L., 2005. Introducing environmental variables in nonparametric frontier models: a probabilistic approach. J Product Anal 24, 93-121.

FAETH P., REPETTO R., KROLL K., DAI Q., HELMERS G., 1991. Paying the farm bill: US agricultural policy and the transition to sustainable agriculture. World Resources Inst, Washington DC, USA. 70 pp.

FÄRE R., GROSSKOPF S., LOVELL C.A.K., PASURKA C., 1989. Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach. Rev Econ Stat LXXI, 90-98.

FÄRE R., GROSSKOPF S., FUKUYAMA H., LEE W.F., WEBER W., ZAIM O., 2004a. New directions in efficiency and productivity. Kluwer Acad Publ, USA. 174 pp.

FÄRE R., GROSSKOPF S., ZELENYUK V., 2004b. Aggregation bias and its bounds in measuring technical efficiency. Appl Econ Lett 11, 657-660.

FÄRE R., GROSSKOPF S., NOH D.W., WEBER W., 2005. Characteristics of a polluting technology: theory and practice. J Econometrics 126, 469-492.

FÄRE R., GROSSKOPF S., WEBER W.L., 2006. Shadow prices and pollution costs in US agriculture. Ecol Econ 56, 89-103.

GOBIERNO DE NAVARRA, 2001. Estudio agroclimático de Navarra. Servicio de Estructuras Agrarias, Sección de Suelos y Climatología, Departamento de Agricultura, Ganadería y Alimentación, Pamplona, Spain. [In Spanish].

HADLEY D., 1998. Estimation of shadow prices of undesirable outputs: an application to UK dairy farms. AAEA Annual Meeting, August 2-5, Salt Lake City, UT, USA. Available at http://ideas.repec.org/s/ags/aaea98.html16 pp.

HAILU A., VEEMAN T.S., 2001. Non-parametric productivity analysis with undesirable outputs: an application to the Canadian pulp and paper industry. Am J Agric Econ 83, 605-616.

HUHTALA A., MARKLUND P.O., 2005. Environmental targets and shadow prices of bad outputs in organic and conventional farming. XIth Congress of the EAAE, Copenhagen, Denmark, 24-27 August. Available at http://orgprints.org/.

KOVACH J., PETZOLDT C., DEGNI J., TETTE J., 1992. A method to measure the environmental impact of pesticides. New York's Food and Life Sciences Bulletin Vol. 139, Cornell Univ, Ithaca, NY.

KRATOCHVIL R., 2002. The contribution of organic agriculture for ground and drinking water conservation. Background Paper, OECD Workshop on Organic Agriculture, 23-26 September, Washington DC.

KRISTOFERSSON D., RICKERTSEN K., 2004. Efficient estimation of hedonic inverse input demand systems. Am J Agric Econ 86, 1127-1137.

KUOSMANEN T., 2005. Weak disposability in nonparametric production analysis with undesirable outputs. Am J Agric Econ 87, 1077-1082.

LAMPKIN N.H., 1994. Researching organic farming systems. In: The economics of organic farming: an international perspective (Lampkin N.H., Padel S., eds). CAB Int, Wallingford, Oxon, USA. pp. 27-43.

LARSEN K., FOSTER K., 2005. Technical efficiency among organic and conventional farms in Sweden 2000-2002: a counterfactual and self-selection analysis. AAEA Annual Meeting, Providence, Rhode Island, July 24-27.

LEE L.K., 1992. A perspective on the economic impacts of reducing agricultural chemical use. Am J Altern Agric 7, 82-88.

LEE J.D., PARK J.B., KIM T.Y., 2002. Estimation of the shadow prices of pollutants with production/environment inefficiency taken into account: a non-parametric directional distance function approach. J Environ Manage 64, 365-375.

LOTTER D.W., 2003. Organic agriculture. J Sustain Agr 21, 59- 128.

MADAU F.A., 2005. Technical efficiency in organic farming: an application on italian cereal farms using a parametric approach. XIth Congress of the EAAE, Copenhagen, Denmark August 24-27. Available at http://orgprints.org/.

OECD, 2001. OECD national soil surface nitrogen balances. Explanatory notes. OECD Secretariat, Paris.

OFFERMAN F., NIEBERG H., 2000. Economic performance of organic farms in Europe. In: Organic farming in Europe: economics and policy (Vol. 5). University of Hohenheim, Stuttgart. 198 pp.

OUDE-LANSINK A.K., CARPENTIER A., 2001. Damage control productivity: an input damage abatement approach. J Agr Econ 52, 11-22.

OUDE-LANSINK A.K., SILVA E., 2004. Non-parametric production analysis of pesticides use in the Netherlands. J Productiv Anal 21, 49-65.

OUDE-LANSINK A.K., PIETOLA K., BÄCKMAN S., 2002. Efficiency and productivity of conventional and organic farms in Finland 1994-1997. Eur Rev Agr Econ 29, 51-65.

PICAZO TADEO A.J., PRIOR D., 2009. Environmental externalities and efficiency measurement. J Environ Manage 90, 3332-3339.

PIOT-LEPETIT I., VERMERSCH D., 1998. Pricing organic nitrogen under the weak disposability assumption: an application to the French pig sector. J Agr Econ 49, 85-99.

ROBERTS W.S., SWINTON S.M., 1996. Economic methods for comparing alternative crop production systems: a review of the literature. Am J Altern Agric 11, 10-17.

ROMBOUGH L., 2002. The grape grower. A guide to organic viticulture. Chelsea Green Publ, UK. 289 pp.

SHAIK S., HELMERS G.A., LANGEMEIER M.R., 2002. Direct and indirect shadow price and cost estimates of nitrogen pollution abatement. J Agr Resour Econ 27, 420-432.

SHEPHARD R.W., 1970. Theory of cost and production functions. Princeton Univ Press, NJ, USA. 308 pp.

SIPILÄINEN T., OUDE-LANSINK A.K., 2005. Learning in organic farming – An application on Finnish dairy farms. XIth Congress of the EAAE, Copenhagen, Denmark, August 24-27.

STOLZE M., PIORR A., HÄRING A., DABBERT S., 2000. The environmental impacts of organic farming in Europe. In: Organic farming in Europe: economics and policy (Vol. 6). Univ. Hohenheim, Stuttgart.127 pp.

TAUER L.W., 2001. Input aggregation and computed technical efficiency. Appl Econ Lett 8, 295-297.

TZOUVELEKAS V., PANTZIOS C.J., FOTOPOULOS C., 2001a. Technical efficiency of alternative farming systems: the case of Greek organic and conventional olive-growing farms. Food Policy 26, 549-569.

TZOUVELEKAS V., PANTZIOS C.J., FOTOPOULOS C., 2001b. Economic efficiency in organic farming: evidence from cotton farms in Viotia, Greece. J Agr Appl Econ 33, 35-48.

ZHENGFEI G., OUDE-LANSINK A.K., WOSSINK A., HUIRNE R., 2005. Damage control inputs: a comparison of conventional and organic farming systems. Eur Rev Agr Econ 32, 167-189.

Appendix

As mentioned earlier, in this work we choose to use a non-parametric methodology, DEA. This method allows us to articulate the expressions above and calculate the directional distance for each unit by the following linear programs, primal and dual formulations in the left and right-hand side, respectively; λ is a $(N \times 1)$ vector of intensity variables. We keep the same notation as [3] for inputs and outputs. We have only distinguished the unit of analysis with the lower index o in order to facilitate the presentation of the restrictions in the dual. As in equation [2], p_{mo} and q_{ro} are the shadow prices of good and bad output of unit o, respectively; w_{no} is the input shadow value.

— Primal formulation

$$\vec{D}_O = Max \quad \beta + \sum_k \lambda_k * 0$$

subject to

$$y_{mo}\left(1+\beta\right) \le \sum_k \; y_{mk}\lambda_k$$

$$b_{ro}\left(1-\beta\right) \ge \sum_k \; b_{rk}\lambda_k$$

$$x_{no} \ge \sum_k \; x_{nk}\lambda_k$$

$$\lambda_k \ge 0$$

$$\beta \ge 0$$

— Dual formulation

$$Min \quad \sum_n \; w_{no}x_{no} - \left(\sum_m \; p_{mo}y_{mo} - \sum_r \; q_{ro}b_{ro}\right)$$

subject to

$$\sum_m \; p_{mo}y_{mo} + \sum_r \; q_{ro}b_{ro} \ge 1$$

$$-\sum_m \; p_{mo}y_{mk} + \sum_r \; q_{ro}b_{rk} + \sum_n \; w_{no}x_{nk} \ge 0, \forall \kappa$$

$$p_{mo}, q_{ro}, w_{no} \ge 0$$