Assessing conventional and organic citrus farming systems eco-efficiency: a metafrontier directional distance function approach using Life Cycle Analysis

Resumen

En este trabajo se analiza la eco-eficiencia de explotaciones citrícolas que operan bajo dos sistemas tecnológicos diferentes, convencional y orgánico. La metodología empleada combina el Análisis del Ciclo de Vida, para estimar los impactos ambientales vinculados al proceso de producción, y el Análisis Envolvente de Datos, para calcular la posición de cada explotación en relación a una frontera formada por las mejores prácticas observadas. Se hace uso del concepto de función distancia direccional, lo que permite estimar la eco-eficiencia con respecto a impactos ambientales concretos, y no sólo para el conjunto de todos ellos. Se emplea también el concepto de metafrontera, al objeto de comparar la eco-eficiencia relativa de cada una de las dos tecnologías empleadas. Los resultados obtenidos muestran una amplia superioridad del sistema de cultivo orgánico en relación al convencional. Un uso eco-eficiente de la tecnología orgánica ('ecológica') representa, en relación a un empleo eco-eficiente de las técnicas de la citricultura convencional, un potencial de reducción de los impactos ambientales del 80% sin empeorar los resultados económicos. En cambio, cuando el comportamiento de las explotaciones citrícolas orgánicas y convencionales se analiza solamente en relación a las mejores prácticas dentro de cada sistema los resultados medios en términos de eco-eficiencia son similares para ambos tipos de explotación.

Summary

In this paper, the eco-efficiency of citrus farms operating under two different - conventional and organic - technological systems is analyzed. The methodology combines Life Cycle Analysis (LCA), to estimate the environmental impacts associated with the production process, and Data Envelopment Analysis (DEA) to estimate the position of each holding in relation to a frontier formed by the best farming practices. The use of the directional distance function concept allows us to calculate farms' eco-efficiency scoring with respect to specific environmental impacts, and not only for the whole of them. The metafrontier concept is also used in order to compare the relative eco-efficiency of each of the two cultivation technologies used. Our results show a wide superiority of the organic farming system in relation to the conventional. An eco-efficient ('green') organic technology represents, in relation to an eco-efficient use of conventional citrus cultivation techniques, a potential reduction of environmental impacts by 80% without worsening economic performance. In contrast, when the performance of organic and conventional citrus farms is only analyzed in relation to best practices within each system, average eco-efficiency scores are similar for both types of farms.

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1. Introduction

Modern agricultural systems can be considered as ecosystems that have been amended in some of their properties to increase productivity (Pretty, 2008), thus providing food and fibre to a rapidly rising human population. The relationship between agricultural systems and natural ecosystems covers a wide range of positive and negative effects (Swinton et al., 2007, Zhang et al., 2007, Power, 2010), and a variety of frameworks have been developed to explore the links between farming and the environment (OECD, 1993, 1999a, 1999b, 2001, Smyth and Dumanski, 1993, EEA, 2005, 2006, Rao and Rogers, 2006, van Cauwenbergh et al, 2007). Is within this context that the concept of agricultural sustainability has been coined to express the concern with the potential consequences of modern farming on the depletion or degradation of natural resources. Nevertheless, as showed by its large number of alternative meanings, sustainability has become an elusive concept. This explains why some experts in the field have consistently argued in favour of developing sustainability indicators, because it "pulls the discussion of sustainability away from abstract formulations and encourages explicit discussion of the operational meaning of the term" (Rigby et al., 2000, p. 5).

Broadly speaking, two main ways of empirically assessing agricultural sustainability have been explored. They are based, respectively, on the identification of management strategies deemed sustainable (i.e. organic agriculture), and in the achievement of a targeted state of the agro-system defined as sustainable and evaluated with a set of indicators. Nowadays, organic farming systems are widely assumed 'sustainable' in the public view or, at least, as relatively more 'sustainable' than conventional ones. The advantages of organic systems with regards to conventional systems concerning the conservation of natural resources and the reduction of environmental impacts per unit of area have been expounded by several meta-analysis of worldwide (Mondelaers et al., 2009) and European-wide research (Tuomisto et al., 2012), even if a wide range of impact variation exists between different impact categories within both types of farming systems. Nevertheless, inferior yields per hectare and lack of economic competitiveness of organic versus conventional farming is an issue that frequently places organic systems at disadvantage and can neutralize some of their environmental benefits (Offerman and Nieberg, 2000, De Ponti et al., 2012; Beltrán-Esteve and Reig-Martínez, 2014).

No single farming system can be considered the best for all circumstances, and a fair assessment of its relative worth mostly depends on the importance assigned to each of the relevant marketable outputs and public goods produced, and also to the monetary costs and negative externalities incurred by farmers (Tuomisto et al., 2012). Therefore, it is of paramount relevance in scientific as in policy-making grounds to perform a joint evaluation of the economic returns and environmental impacts produced by farms operating under conventional and organic agricultural systems, in order to obtain a sound basis for an all-encompassing comparison between both systems. The concept of eco-efficiency has received significant attention in the sustainable development literature because it provides researchers and stakeholders with a useful tool to reach this goal (Zhu et al., 2014, Govindan et al., 2014).

According to the OECD (1998), eco-efficiency expresses “the efficiency with which ecological resources are used to meet human needs. It can be interpreted as the relationship between one output and one input: the output represents the value of the goods or services produced by a company, industry or economy as a whole, while the input represents the sum of environmental pressures generated by the company, industry or economy” (p.7). As a result, eco-efficiency can be interpreted as a ratio or coefficient that measures the relationship between the economic outcome of a production unit (i.e. sales value, value added, output, etc.) and its environmental impact (WBCSD, 2000).

The concept of eco-efficiency is connected to the more encompassing notion of sustainability, but it must be recognised that an improvement in the eco-efficiency coefficient does not necessarily guarantee sustainability (Huppes and Ishikawa, 2005). In any case pursuing eco-efficiency remains important because it is frequently the single most cost-efficient way of reducing environmental pressures, and because targeting improvements in eco-efficiency is politically more feasible than implementing other policy measures that are likely to restrict economic activity (Kuosmanen and Kortelainen, 2005). Also, it must be taken into account that promoting eco-efficiency has a high likelihood of success, as very often companies are not operating at their economic efficiency frontier. This opens a window of opportunity for management to make net costs savings, while simultaneously reducing environmental impacts (Ekins, 2005).

A workable approach to analyse sustainability at farm level thus consists in evaluating whether individual farmers are making an efficient use of natural resources in order to achieve their economic objectives. Efficient use of natural resources translates into efficient use of polluting inputs and adoption of those cultivation techniques intended to minimise negative environmental impacts. The notion of efficiency can be adapted to this context, and a production unit can be deemed eco-efficient when no improvement can be achieved in relation to any environmental objective without worsening performance in other environmental or economic objective, thus implying the existence of a ‘best practice frontier’ acting as a benchmark (Kuosmanen, 2005). Computing eco-efficiency ratios at farm level, the environmental and economic performance of farmers can be compared with that of their most efficient colleagues operating on the ‘efficient frontier’, in order to analyse differences in management and their environmental consequences.

We aim in this paper to compare the eco-efficiency of Spanish conventional and organic citrus farming systems. We start by using a Life Cycle Analysis (LCA) assessment’s methodology to estimate farm-level environmental impacts. In accordance with LCA common practice our analysis goes beyond the direct environmental impact of cultivation to include also the environmental pressures arising from inputs’ manufacturing. Then we proceed to compute farms’ eco-efficiency scores, using a Data Envelopment Analysis approach, and compare each system-specific best practice frontier with regards to a metafrontier that envelops both. .

We adopt a ratio indicator of eco-efficiency defined at farm level, with the value of production in the numerator and a composite measure of environmental impacts (i.e. eutrophication, global warming etc.) in the denominator, according to WBSCD (2000). As no self-evident pattern of weights exists for this set of environmental impacts, we have opted for an endogenous computation of weights, using Data Envelopment Analysis (DEA) to that effect.

Our analysis starts by considering the main characteristics of LCA, paying particular attention to the stream of literature to the literature that in recent years have mixed DEA with LCA to assess farming eco-efficiency. Then we take the analysis a step further, by using directional distance functions to model farming technology, thus being able to compare farming systems performance not only with regards to the relationship between economic returns and a whole set of environmental impacts, but also in relation to some specific impacts, while assuming constant for the time being the remaining environmental pressures. Therefore we are able to compare the eco-efficiency of organic and conventional systems from a Life Cycle Analysis perspective in broad terms, but also to discover the advantages of each system concerning particular features of its environmental performance.

After this introduction, we proceed in Section 2 to expound our methodological approach, while in Section 3 we show the broad features of both citrus cultivation systems, describe variables and sample data, and perform Life Cycle Analysis. Section 4 is devoted to the computation of DEA model, and presentation and discussion of our results, and Section 5 sets out the conclusions on the basis of our findings.

2. Methodology.

2.1. An introduction to LCA and DEA methodology

A basic tenet of our methodological approach is the combination of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) to set up a comparison of eco-efficiency for two technologically different farming systems – organic and conventional citrus farming -. LCA was first proposed in the late 1960s and early 1970s and has evolved as a prevailing quantitative tool to measure environmental impacts, undertaking a substantial degree of international standardization in the process (Arvanitoyannis, 2008, Pryshlakivsky and Searcy, 2013, Chang et al., 2014). LCA is a methodology that basically converts inventory data of outputs and inputs of a system to a reduced number of environmental indicators. A widely used definition of LCA states that "LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle 'from the cradle to the grave' . . . covers all types of impacts upon the environment, including extraction of different types of resources, emission of hazardous substances and different types of land use" (Guinée et al., 2004, p.5-6).

LCA traditionally consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. The first phase, defining its scope, require drawing the system's boundary and establishing a functional unit of analysis The boundary establishes the significant processes to be included in the analysis and the limits between the technical system and the environment. The functional unit is the unit of quantitative measurement of the functions provided by the product or service being analyzed. The second phase of the life cycle inventory stage, involves collecting data with regards to inputs and emissions associated with each stage of the product life cycle. Afterwards, Life Cycle Impact Assessment (LCIA) is the phase in which inputs and emissions previously listed in the inventory stage are grouped into specified environmental impact categories. Finally, the interpretation phase analyses the results and put forwards recommendations[1].

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[1] See Guinée et al. (2004) for a detailed operational description, Finnveden et al. (2009) for a thorough review of recent developments in LCA methodology, and Rüdenauer et al. (2005) for a presentation of LCA as a method for eco-efficiency analysis.

Most of the time, when LCA has been applied to a number of production facilities, average inventory data were used or average environmental impacts were computed. Nevertheless, data variability concerning operational tasks may lead to high standard deviations in some environmental impacts, questioning the reliability of the whole exercise., For this reason, LCA was applied, in some cases, to various categories or business units (Basset-Mens et al., 2009). The greater the number of individual observations to which the LCA is applied the higher the representativeness of the analysis, but, if not synthesized in any way, results are unlikely to be used as a basis for decision-making. This practical shortcoming has been one of the main arguments pointing to the convenience of a joint implementation of LCA and Data Envelopment Analysis (DEA), in order to handle information belonging to a large number of individual production processes and to perform eco-efficiency analysis, thus avoiding the use of average inventory data (Lozano et al., 2009, Iribarren et al., 2011).

DEA is a nonparametric technique originally designed to compute efficiency indices for a number of public or private entities (Charnes et al., 1978). DEA defines the efficiency score of a decision unit by the value of a ratio that transforms its vector of inputs into its vector of outputs. Observed input and output quantities are employed in the calculation and no price information is necessary to aggregate them, which is a considerable advantage when environmental impacts are involved because of the lack of adequate measures to price environmental impacts. The weights employed for the aggregation of inputs and outputs are determined endogenously through an exercise of mathematical optimization in which each DMU performance is being compared with the productive behavior of some other DMUs in the sample that are deemed efficient. The optimization program chooses these weights in order to obtain the highest ratio for the DMU being analyzed, this is why the DEA approach has been called a ‘benefit of the doubt’ approach (Cherchye et al., 2007). A detailed explanation of the methodology of DEA can be obtained in Cooper et al. (2007).

The conventional DEA analysis allows the researcher to assess the performance of individual DMUs taking only into account observed quantities of marketable inputs and outputs. However, a distinctive research stream has focused on the employment of this technique for dealing with the environmental consequences of production processes. Nowadays, the DEA literature can boast a large number of papers dealing with environmental issues[2].

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[2] Allen (1999) outlined the potential and difficulties of using DEA in an ecological context, also Dyckhoff and Allen (2001), and Zhou et al. (2008) have surveyed and classified one hundred studies published from 1983 to 2006 within this stream of research, which is rapidly growing. Zhang and Choi (2014) have surveyed the use of directional distance functions for the analysis of environmental topics.

A growing literature has approached the analysis of the environmental impacts of economic activity by using a combined LCA-DEA methodology[3]. The most common approach in such cases consists in employing a DEA-based production model to assess technical efficiency for each DMU, and then to determine the projected efficient input levels for inefficient DMUs. In a second stage LCA is performed for the virtual or projected efficient input/output levels, and also for observed levels, and comparisons are made. Authors then draw conclusions concerning the unnecessary environmental impacts resulting from lack of technical efficiency in the production process. We believe that this approach presents some shortcomings. It is true that correcting technical inefficiency is normally conducive to less emissions of pollutants and less waste, and therefore to an improvement in eco-efficiency. Nevertheless, technically efficient DMUs may display widely different inputs mix and, correspondingly, may give rise to widely different levels of environmental impacts.

Our methodological approach is framed within the line of research work that have considered environmental impacts as inputs in DEA models and define an eco-efficiency indicator that takes into account simultaneously the economic behavior and the environmental performance of the units analyzed (Kuosmanen and Kortelainen, 2005). In such an impact-oriented DEA optimization model, different environmental performances of technically efficient DMUs are compatible with the same economic outcome and, therefore, may represent distinctly different eco-efficiency scores.

In this paper LCA is employed as an auxiliary tool to set up the stage for a DEA-based eco-efficiency analysis. In the first place we use LCA to determine the potential environmental impact arising from each production process. Then, in a second stage, we employ DEA to compare the mix of economic outcome obtained, and potential environmental impact exerted, by individual producers in order to compute their score of relative eco-efficiency. The benchmark corresponds to those decision making units (DMUs) operating on the technological frontier(i.e., the eco-efficient producers). Furthermore, the use of directional distance functions allows us to take the analysis a step further and to assess not only global eco-efficiency of a DMU, but also the eco-efficiency displayed in the management of particular environmental impact categories. Also, paying attention to the characteristics of those farms deemed fully eco-efficient makes it possible to establish which particular production techniques are more appropriate to maximize economic value per unit of environmental impact. Moreover, as we pointed out in the introduction, eco-efficiency analysis is performed

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[3] See, for example, Lozano et al., 2009, Vazquez-Rowe et al. (2010, 2012), Iribarren et al.(2010, 2011), Sanjuan et al. 2011, Mohammadi et al (2013), Lorenzo-Toja et al., 2015.

recognizing that there is technological heterogeneity between groups of DMUs by using the concept of metafrontier, as an envelop of the different group frontiers, allowing a comparison of eco-efficiency of group technologies in regard to the metatechnology (O'Donnell et al., 2008).

2.2. Eco-efficiency and DEA methodology.

We describe in this Section the building blocks of our methodological approach, introducing those concepts and mathematical programs allowing the quantitative measurement of eco-efficiency and setting the stage for an assessment of eco-efficiency at farming system level.

2.2.1. Eco-efficiency, metatechnology, and the directional metadistance function.

We adapt the methodological approach in Beltrán-Esteve et al. (2014) to compute farm-level eco-efficiency for a set of citrus farms made up of two sub-sets of organic and conventional farms, and to draw comparisons regarding the eco-efficiency of both farming systems.

We assume that we are able to observe the economic performance of a set of k=1,…,K producers, represented by the output economic value v, and their environmental performance, represented by a series of n=1,…N damaging impacts on the environment, denoted by the vector $d=(d_1,\dots,d_N)$.

Eco-efficiency is defined as a ratio between economic value and an aggregate of damaging environmental impacts arising from farms' economic activity; it represents a sort of environmental-productivity ratio approach (Huppes and Ishikawa, 2005). Formally, for a producer k, eco-efficiency is

$$\mathrm{Ecoefficiency}_k = \frac{\mathrm{Economic\ Value_k}}{\mathrm{Damaging\ Environmental\ Impacts_k}} = \frac{\mathrm{v}}{\mathrm{D(d)}} \qquad (1)$$

D being an aggregator function of the N damaging environmental impacts into a single score. The most common aggregator function is a linearly weighted average of particular impacts.

While some studies may weight environmental impacts with external information based on experts' opinion, in this paper weights of environmental impacts are generated endogenously at the producer level using DEA, which shows the overall performance of each producer under the most favorable light. In this manner, we are using eco-efficiency as a relative concept, in which the optimal or efficient environmental impact is largely subject to technological constraints and a producer eco-efficiency should reflect its performance relative to the other producers in the same industry (Chen, 2014: 44).

For a given industry (i.e. citrus farming) we define the metatechnology as the envelopment of all known technologies (Hayami and Ruttan, 1970). It can be represented by the *damaging environmental impact requirement metaset* (ERMS), which displays all the combinations of damaging environmental impacts, d, that allow to obtain at least economic value v,

$$\text{ERMS}\ (\text{v}) = \langle \text{d} \mid (\text{v}, \text{d}) \in \text{T} \rangle \tag{2}$$

where T represents all the feasible combinations of economic value and environmental impacts given the present state of the technology.

The *directional metadistance function* (MD) provides another representation of the metatechnology[4] and is a very flexible tool for assessing eco-efficiency, measuring the distance with respect to the metafrontier[5] of a particular observation (v,d), along a path defined by the researcher by selecting the direction vector, g = (g_v, -g_d). Formally,

$$\text{MD}\left[\text{v}, \text{d}; \text{g}=(\text{g}_\text{v}, \ -\text{g}_\text{d})\right] = \text{Sup}\ \langle \beta \mid \left(\text{d} - \beta \text{g}_\text{d}\right) \in \text{ERMS}(\text{v} + \beta \text{g}_\text{v}) \rangle \tag{3}$$

The directional metadistance function measure the potential increase in economic value, in a direction g_v, and the simultaneous potential reduction of damaging environmental impacts in a direction -g_d. Making use of its flexibility, in defining direction vector we may build up two main kinds of eco-efficiency indicators both of them evaluating a potential reduction in damaging environmental impacts while keeping economic value constant.

First, we specify the direction vector as g_{all}=(g_v , -g_d)=(0, -d), and compute the maximum *proportional reduction* of all damaging environmental inputs consistent with the metatechnology while economic value is not reduced. This is what we call *radial eco-efficiency*, and the directional metadistance function can be represented in this case as:

$$\text{MD}_\text{all}\left[\text{v}, \text{d}; \text{g}_\text{all}=(0, \ -\text{d})\right] = \text{Sup}\ \langle \beta_\text{all} \mid \left(1 - \beta_\text{all}\right)\text{d} \in \text{ERMS}(\text{v}\ ) \rangle \tag{4}$$

The value taken by function (4) is always equal to or greater than zero, with a score of zero indicating eco-efficiency, meaning that proportional reduction in damaging impacts is not feasible without a concomitant decrease in economic value. Furthermore, increasing values of this function imply a higher potential for environmental impacts reduction and a greater eco-inefficiency of that producer.

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[4] The theory of directional distance function, introduced by Chambers et al. (1998), is summarised by Färe and Grosskopf (2000).

[5] The metafrontier represents the eco-efficient combinations of economic value and damaging environmental impacts given the state of the technology, T.

Within a DEA framework, the mathematical optimization program required to calculate the directional metadistance function for farm k’ in expression (4) is:

$$\text{maximize}_{\beta_{\text{all}}^{k'},\lambda^k}\ \beta_{\text{all}}^{k'} \qquad k' \in k=1,\dots,K \tag{5}$$

subject to:

$$v^{k'} \leq \sum_{k=1}^{K} \lambda^k v^k \qquad \text{(i)}$$

$$(1-\beta_{\text{all}}^{k'}) d_n^{k'} \geq \sum_{k=1}^{K} \lambda^k d_n^k \qquad n=1,\dots,N \qquad \text{(ii)}$$

$$\lambda^k \geq 0 \qquad k=1,\dots,K \qquad \text{(iii)}$$

$\beta_{\text{all}}^{k\prime}$, represents the maximum potential reduction than can be achieved by farm k’ when all environmental impacts are taken together. By way of example, if $\beta_{\text{all}}^{k\prime}$ takes a value equal to 0.40, it means that farm k’ can reduce all its environmental impacts by 40 % and obtain the same economic value, *when using the* most environmental-friendly available techniques.

Secondly, we define a kind of *impact-specific eco-efficiency indicators*, when we aim to assess the maximum potential reduction for a particular environmental impact (or a group of environmental impacts), denoted by i, while the remaining environmental impacts, denoted by –i, and the economic value, v, are kept constants. In such a case, we specify the direction vector as $g_i=(g_v, -g_d)=[0, -(d_i, 0)]$, and the directional metadistance function as,

$$MD_i\left[v, d; g_i=(0, \langle -d_i, 0\rangle)\right]=\text{Sup}\left\langle \beta_i \,\middle|\, [(1-\beta_i)d_i, d_{-i}] \in ERMS(v)\right\rangle \tag{6}$$

This function is also lower-bounded to zero, which denotes eco-efficiency, and its value is always equal or greater than the radial eco-efficiency score in expression (4).

The optimization program required to compute the specific directional metadistance function form firm k’ in expression (6), in which only a group of environmental impacts, i, is being reduced is,

$$\text{maximize}_{\beta_i^{k'},\lambda^k}\ \beta_i^{k'} \qquad k'\in k=1,\dots,K \qquad (7)$$

subject to:

$$v^{k'} \leq \sum_{k=1}^{K} \lambda^k v^k \qquad (i)$$

$$(1-\beta_i^{k'})d_i^{k'} \geq \sum_{k=1}^{K} \lambda^k d_i^k \qquad i \in n; i \notin -i \qquad (ii)$$

$$d_{-i}^{k'} \geq \sum_{k=1}^{K} \lambda^k d_{-i}^k \qquad -i \in n \qquad (iii)$$

$$\lambda^k \geq 0 \qquad k=1,\dots,K \qquad (iv)$$

$\beta_i^{k'}$, represents the maximum potential reduction than can be achieved by farm k' with regards to the environmental impact, or group of impacts, i , while economic value and the other impacts do not get worse. In this case, if $\beta_i^{k'}$ takes a value o 0.55 this figure indicates that producer k' can reduce damaging impacts i by 55 % without increasing any other environmental impact or reducing production value. The potential maximum reduction for a specific impact i is at least as great as the maximum proportional reduction. Thus, if it feasible to proportionally reduce the whole set of environmental impacts by 40 % , it is also feasible to reduce any single impact (or group of impacts) by at least 40%.

2.2.2. Group technology, directional distance function and eco-efficiency

We have defined the metatechnology as the envelope of all known technologies available in an industry. Taking into account that, because of constraints imposed by technical or legal considerations, not all known technologies are available to producers belonging to certain groups, we can define *group technologies* and eco-efficiency scores with respect producer´s own group technology (O'Donnell et al., 2008).

Producers of our sample may be split into several groups[6]. For each group h, we can define the group technology, T^h, as all the feasible combinations of economic value and damaging environmental impacts that can be generated by farms in group h. The directional distance functions can be used to assess the eco-efficiency of producers in group h with respect their own group h technology.

The maximum proportional reduction in all the damaging environmental impacts compatible with the economic value obtained by a producer k' belonging to group h with respect to his own group h technology, $\beta_{\text{all}}^{hk'}$, is obtained by solving for k' the optimization program (5) in which K represents the producers of group h. This is the *radial group eco-efficiency* measure. In a similar way, for a producer k' belonging to group h, the maximum potential reduction in one

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[6] A complete formulation of the group technology and directional distance function with respect group technology can be found in Beltrán-Esteve et al. (2014)

environmental impact (or a group of them) i, while other impacts –i and economic value, v, stay constants, with respect their own group technology, $\beta_{\mathrm{i}}^{hk'}$, is obtained by solving for k' the optimization program (7) where K represents the producers of the group h. This is the *impact-specific group eco-efficiency* measure.

It is worth to noting that the directional distance functions computed in regard to the group h technology are always equal to or lower than the directional metadistance functions computed relative to the metatechnology. Maximum potential damaging environmental impact reduction with respect a restricted, or group-specific, technology is lesser than potential reduction when it is considered against the envelope of all known technologies, or metatechnology.

We have defined eco-efficiency indicators as the distance of a producer to the best practice frontier; in such a way, the higher the value of $\beta^{k'}$ the lesser the eco-efficiency of k'. A zero value means that producer k' is onto the technological frontier and no impacts reduction is feasible. On the other hand, if it takes a value of 0.20 it means that the producer can reduce his environmental impact by 20% without reducing production; in other words, an eco-efficient use of the available technology would allow him to obtain the same economic value with only 80% of the environmental damage it generates. This last formulation is a more convenient way of looking at eco-efficiency; in this way we obtain (1-$\beta^{k'}$). Furthermore, for an eco-efficient producer it will take a value of one, indicating that all 100% of environmental impacts are required to produce the economic value.

2.2.3. Metatechnology ratios and group technology eco-efficiency assessment

Rather than simply providing an appraisal of producer performance regarding economic-environmental trade-offs, we can contribute an assessment of the advantages and disadvantages of alternative group technologies as regard their eco-efficiency in the management of overall or specific damaging environmental impacts. The *metatechnology ratio* assesses how close the technology of group h is to the unrestricted technological frontier or metatechnology (Beltrán-Esteve et al. 2014).

When considering a direction vector that proportionally reduces all the damaging environmental impacts, the radial *metatechnology ratio for group h* is formalized as:

$$\mathrm{Metatechnology\ ratio}_{\mathrm{all}}^{\mathrm{hk'}}\left[\mathrm{v,\ d;\ g_{all}}=(0,\ \text{-d})\right]=\frac{\mathrm{Metaecoefficiency}_{\mathrm{all}}^{\mathrm{k'}}}{\mathrm{Ecoefficiency}_{\mathrm{all}}^{\mathrm{hk'}}}=\frac{\left(1\text{-}\beta_{\mathrm{all}}^{\mathrm{k'}}\right)}{\left(1\text{-}\beta_{\mathrm{all}}^{\mathrm{hk'}}\right)} \tag{8}$$

Going back to our example, farm k' with a distance to the metafrontier of 0.40, has a metaeco-efficiency of 0.60; the group-specific eco-efficiency is of 0.80, reflecting a distance of 0.20 with respect to the group h frontier. Therefore, the metatechnology ratio of farm k' belonging to group h is 0.75, indicating that only 75% of the eco-efficient environmental impacts corresponding to the group h frontier will be needed if the production were operated with a no-restricted technology; distance of group h frontier to the metafrontier is 0.25, implying a damaging impact excess of 25%.

Alternatively, we can assess the performance in the management of a specific environmental impact, or group of impacts, i, in terms of eco-efficiency relative to group h frontier, and the metaeco-efficiency with respect to the metafrontier and obtain, in a very similar fashion, the *impact-specific metatechnology ratio* for the group h; formally, for impact i is:

$$\text{Metatechnology ratio}_i^{hk'}\left[v, d; g_i=(0, \langle -d_i, 0\rangle)\right]=\frac{\text{Metaecoefficiency}_i^{k'}}{\text{Ecoefficiency}_i^{hk'}}=\frac{(1-\beta_i^{k'})}{(1-\beta_i^{hk'})} \quad (9)$$

Impact specific metatechnology ratios assess how close is the group h frontier to the metafrontier in terms of the management of the damaging environmental impact i.

This approach provides a useful breakdown of a measure of eco-efficiency defined with respect to the metafrontier, the metaeco-efficiency, into the product of the eco-efficiency with respect to the group h frontier and the metathecnology ratio of group-h, which constitutes a group-h technology eco-efficiency assessment (O'Donnell et al. 2008). In this manner, it is possible to separate the eco-inefficiencies that can be attributed to inadequate management of the producer, within a group-specific technological context from those responding to the shortcomings of the technology used. This relationship could be formalized as:

$$\text{Metaecoefficiency}_i^{k'}=\text{Ecoefficiency}_i^{hk'}\cdot\text{Metatechnology ratio}_i^{hk'} \quad (10)$$

for impact-specific indicators and in a similar way for radial indicators.

3. Ecological and conventional citrus farming: data and variables

3.1. Differential characteristics of organic versus conventional citrus farming in Spain

Organic citriculture presents technical aspects that are different from those in conventional citrus farming, the main difference being that organic farms cannot employ fertilizers obtained by chemical synthesis, instead organic citrus orchards uses compost manure, supplemented with complex organic materials. An organic citrus orchard maintains biodiversity through the ground cover (i.e. alfalfa, wild grasses), and by using hedgerows, which also prevent wind damage and host populations of beneficial insects and birds. Pruning remains are crushed and left as waste compost on the surface in organic farms, thereby restoring a lot of nutrients. By contrast, the conventional practice of burning of pruning waste causes large loses of organic matter and increases CO_2 emissions. Also, organic citrus farms retain moisture better and make a better use of limited water resources. A description of technical aspects of organic citriculture may be found in Porcuna et al. (2010) and in Domínguez-Gento (2008).

Organic citrus farming still represents a small proportion of total farmland devoted to citrus production in the region of Valencia, which is the main production area in Spain. According to official statistics (MARM, 2010), the surface area devoted to citrus farming in 2010 in the region represented a total of 178,361 hectares, while organic citrus groves were estimated to cover only 1,004 hectares.

The slow diffusion in Spain of organic citrus farming can be explained by the difficulties to isolate the small sized organic citrus farms from intensive plantations, a long history of intensive production, lack of appropriate distribution channels for organic produce in the domestic market, and the higher variable costs incurred in organic production (Peris and Juliá, 2005). But despite factors hindering the shift from conventional to organic citrus production, some farmers have been driven to adopt organic techniques. Recent research has shown that the main motivations to adopt organic farming are: concerns for the environment and the wellbeing of future generations, an aspiration to produce high quality output and a willingness to reduce dependence on agrochemicals, with pecuniary aspects playing a less important role (Beltrán-Esteve et al. 2012).

3.2. Data and variables

The data used in this paper come from a survey designed for a larger research project aimed at analyzing both the economic and environmental performance of conventional and organic citrus farming in the Spanish region of Valencia. In 2009, all 203 organic citrus farmers registered as certified ecological producers in Valencia were contacted and 153 of them agreed to answer a questionnaire. Furthermore, 129 conventional citrus farmers, from a control group of two hundred, completed the survey. Beltrán-Esteve et al. (2012) provide more detail on this issue. After removing observations with missing data and some outliers, the sample comprised 98 organic citrus farms and 96 conventional citrus farms.

For each of these growers we have measured the economic performance as the value of citrus production, and the environmental performance by six environmental impacts obtained by performing a Life Cycle Analysis following the usual phases, briefly summarized in which follows.[7] As regards *boundary and functional unit determination*, in this paper the boundary of the system has been defined in order to include the production of fertilizers, herbicides, and plaguicides, the use of farm machinery, which includes the production of fuels, and citrus cultivation, which includes tasks involving inputs application. On the other hand, we have disregarded all processes related to the production of capital goods such as machinery and buildings. The functional unit adopted is one hectare. Concerning *inventory analysis*, all inputs (materials and energy) and outputs (emissions to air, water or soil) associated to the production system and to the other stages within the system's boundaries have been collected, and are expressed in terms of the functional unit. Regarding *impact assessment, s*ix different impact categories have been considered in this paper: global warming, ozone layer depletion, eutrophication, ecotoxicity affecting flora and fauna, and carcinogenic and non-carcinogenic human toxicity. The result for each impact category is determined by multiplying the aggregated resources used and the aggregated emissions of each substance obtained in the inventory stage by a characterization factor. This factor is specific for each impact category to which can potentially contribute (Basset-Mens and van der Werf, 2005).

Table 1 provides information on the main descriptive statistics of the variables used in our eco-efficiency analysis for both citrus systems. First, concerning *economic performance*, it should be noted that there is a significant difference in favor of conventional farms resulting from higher yields, which is not being offset by a higher sale price of organic products. Revenue per hectare in organic farms accounts, on average, for only three quarters of that obtained by conventional farms. Secondly, against this economic disadvantage, and according to LCA impact categories, organic farms display a much more favorable balance in all *environmental* impacts, except for eutrophication in which no statistically significant differences can be observed. Notable differences appear in eco-toxicity and human carcinogenic toxicity, where organic farms generate, on average, less than 1% of the impacts generated by conventional ones. Even for global warming potential, where differences are not so marked, the advantage enjoyed by organic farms is still overwhelming, generating only 13% of the impacts of conventional farms.

But, is organic farming more eco-efficient than conventional farming? Or rather, may best economic results on conventional farms outweigh their worst environmental performance? In any case, it seems essential to isolate, given the significant deviations from the mean in all

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[7] Further technical detail can be requested from the authors.

variables, which part of the results obtained by different farms corresponds to farmers' eco-efficient performance, and how much is attributable to the characteristics of each farming system. Answering these questions demands a thorough eco-efficiency analysis.

4. Results

From the data of the variables listed in Table 1 for the 194 farms in our sample, and using the DEA methodology described in section 2.2, we have calculated directional metadistance functions (DMDF) and directional distance functions (DDF) for each farm. Solving program [5] we have obtained metadistance functions relative to the metatechnology (expression 4) in a direction that reduces all environmental impacts for each citrus farmer k'. In addition, this program has also been used for the calculation of radial distances of each grower k' to its own group frontier. But in this case only farms belonging to each particular farming system, either organic or conventional, have been considered in the corresponding optimization exercise. Then, using expression [8] we have computed the metatechnology ratio.

Furthermore, program [7] has been used to compute impact-specific eco-efficiency indicators for each farm k'. To this end we have proceeded to calculate the directional metadistance distance function (expression 6) with respect to all citrus farms, and the directional distance function with respect to farms of each group, and also the corresponding metatechnology ratios. Specifically, nine directions have been specified. One for each environmental impact considered individually, and three more in which the impacts effects on the environment are grouped attending to their global character (GWP and ODP are jointly considered), local or regional character (eutrophication and ecotoxicity are taken together), and their effect on human health (carcinogen and non-carcinogen human toxicity). Recall that in each of these cases what is evaluated corresponds to the maximum potential reduction in the specified impact or impacts, while the rest of impacts and economic outcome remain constant. Table 2 shows the average of these estimates for farms operating in each of both systems.

Radial indicators show maximum proportional reduction in all damaging environmental impacts taken together. The first thing that stands out when this type of indicators are calculated is the high eco-inefficiency of citrus production. When farms performance is benchmarked with regard to best practices in their own farming system, we find that conventional farms could reduce all environmental impacts by 54% without worsening its economic performance, while potential reduction of environmental impacts for organic farms amount on average to 58%. Thus, the average distance of farms to their most eco-efficient counterparts within their own system is quite similar. However, it should be noted that the

DDF of conventional and organic farms are not directly comparable since they are computed with respect to different technologies of reference. In this sense, results obtained regarding the common metafrontier (DMDF) of both groups of farms, show a different picture. Conventional farms could be able to reduce pressures by 90.9%, compared to 58% for organic farms. In other words, if operating as the most eco-efficient growers do, conventional farms could achieve the same economic results with only 9.1% of the damaging environmental impacts observed for this type of farms. The corresponding figure for organic farms is 42%. Using expression [10], these relevant differences can be explained either by the different eco-efficiency performance of producers of each system (1-DDF), or by technological differences between systems concerning eco-efficiency as reflected in the metatechnology ratio (MTR). As we have seen, eco-efficiency within each system is pretty much like, but what about the eco-efficiency of the systems? The MTR of the organic farming system takes a unity value, indicating that the organic system frontier overlaps with the metafrontier. By contrast, with a MTR of 0.199, the conventional system frontier is far from the metafrontier. Even when used efficiently, conventional technology involves an excess of 80% in the generation of damaging environmental impacts regarding those farms deemed more eco-efficient, which in this case are represented by the set of organic farms operating on the best practice metafrontier.

Now, a question may be raised concerning whether these results are equally valid when we are concerned only with certain environmental impacts. It is important to know if farms' management shows differences with regards to different types of environmental pressures, and to compute the distance to the metafrontier of each system's frontier when these pressures are assessed independently. To answer these questions we look at the *impact-specific indicators* shown in Table 2.

An assessment of farmers' performance regarding their own technology highlights the most eco-efficient joint management of impacts of regional nature by conventional farmers, while no significant differences between both groups appear in either the joint management of impacts of global nature or concerning human toxicity. Underperforming organic growers could reduce environmental impacts of regional nature by 68.4%, while for conventional ones potential reduction amounts to 55.5%. When we pay attention at individual impact indicators it may be stressed the most eco-efficient management of GWP, eutrophication and non-carcinogenic human toxicity by conventional farmers, while only in the management of the carcinogenic human toxicity they are surpassed by their organic competitors. The highest levels of eco-efficiency with respect to its own technology achieved by conventional producers could be associated with less variability in economic returns linked in turn to more effective pest control. It must be recalled that they face fewer restrictions on the use of pesticides. Focusing our attention on the eco-efficiency with which farmers manage the various environmental impacts, we observe that conventional producers manage more efficiently the problems associated with eutrophication and are not so good when dealing with carcinogenic human toxicity and with ecotoxicity; for their part organic farmers obtain their best results with regards to ozone depletion and carcinogenic human toxicity.

We obtain a different perspective when farmers' performance is assessed with regards to a non-restricted technology (i.e. the metatechnology). Results obtained with DMDF show that despite the large potential that still exists for the reduction of the environmental impacts posed by organic farms, these farms display eco-efficiency scores substantially better than those exhibited by conventional farms for all specific indicators considered. This is reflected in the metatechnology ratios, which show a clear superiority in the eco-efficiency of the technology used by the organic system relative to the conventional one in all indicators analyzed. Whatever the environmental impact, MTR of organic farms take a unity value. On the other hand, the conventional system underperforms in comparison, with high eco-inefficient scores in all types of impacts, though there are notable differences between them. The shortest distance from the conventional technology to the metatechnology occurs in eutrophication, with an MTR of 0.21. It means that the best efficient performance that conventional farms would be able to achieve under the restrictions imposed by this technology could still be improved by 79% to reach the performance of farms operating on the metafrontier. The scoring of the rest of specific indicators shows that the potential for improvement with a change to organic production is even greater.

In short, when we quantify the potential benefits that may be obtained in terms of eco-efficiency with a shift to organic techniques in citrus production, results are striking. An eco-efficient use of green technology means, in relation to an eco-efficient conventional technology, a potential reduction of environmental impacts of 80% without worsening economic performance, a reduction that reaches even more than 95% for impacts related to the depletion of the ozone layer, ecotoxicity and human toxicity.

5. Conclusions.

We have aimed in this paper to combine Life Cycle Analysis and Data Envelopment Analysis to assess the performance of citrus farmers with regards to eco-efficiency.

Empirical studies aimed to assess eco-efficiency in agriculture have mostly assumed that farms share the same production technology. However, this assumption is wholly inappropriate when different groups of farms face different technological restrictions, as is the case of conventional and organic citrus farms. When technological heterogeneity exists, eco-efficiency scores computed against different and idiosyncratic technological frontiers cannot be meaningfully compared. The notion of a metafrontier representing an unrestricted technology that envelops each system particular technology helps to overcome this problem, and permits to rank the eco-efficiency of technologically heterogeneous groups of producers. Comparing the technology of each group with the metatechnology allows us to assess the relative eco-efficiency of the farming systems. Furthermore the use of directional distance functions allows us to assess technological differences regarding the management of specific environmental impacts

Using observations for a sample of 194 Spanish citrus farms as regards their economic performance –measured by the value of production- and their environmental performance –measured by six LCA impacts- we have been able to obtain relevant findings concerning not only global eco-efficiency in broad terms, but also impact-specific, and group-of-impacts-specific assessment. In the first place our conclusions point to a high and similar level of average farmers' eco-inefficiency in both citrus systems when the benchmark is their own technology. Results are different when a common metafrontier for both groups of farms is adopted as a reference. Then, conventional farms score much worse than organic ones: they should be able to reduce their damaging environmental impacts by 90.9%, compared to 58% for organic farms. As regards the eco-efficiency of the systems technology, a metatechnology ratio of one for the organic technology indicates that organic frontier overlaps with the metafrontier, i.e., organic technology is fully eco-efficient. On the other hand, the gap between the conventional farms best practice frontier and the metafrontier is large and indicates a potential saving in environmental impacts resulting from the conversion from conventional to organic farming of around 80%.

Regarding the management of specific environmental impacts by farmers in their own technology, conventional farmers behave better concerning the eco-efficient joint management of impacts of regional nature, particularly in eutrophication, and do the worst as regards ecotoxicity, while organic farmers manage better the impacts of global nature, in particular ozone. More interesting, in relation to the management of specific environmental impacts by farming systems, the organic system is eco-efficient irrespective of the impact analyzed, whereas co nventional system distances from the metafrontier are very large, in particular as regards human toxicity and ecotoxicity.

These results points, in the first place, to the need of spending a substantial amount of effort on the part of agricultural authorities to improve technical advice to citrus farmers, both conventional and organic, to bridge the observed gap with best practice environmental practices, which is relatively wide for the average citrus farmer.

Nevertheless, actively promoting the adoption of organic farming would undoubtedly improve the balance between economic outcomes and environmental impacts in citrus farming. Our research main conclusion has to do with the superiority in terms of eco-efficiency displayed by the organic farming system when compared with the conventional one. It means that conversion to organic must be considered as a legitimate goal for public policy. A stream of research has concluded that the main obstacles to the diffusion of organic citriculture have to do with inferior profitability of organic citrus farming (Juliá and Server, 2000, Peris et al., 2005, Peris and Juliá, 2006). Current price differentials in favour of organic produce do not compensate for lower yields and higher variable production costs. Therefore, achieving higher technical efficiency in organic farms could substantially contribute to improve their chances in competition with more traditional conventional farms (Beltrán-Esteve and Reig-Martínez, 2014), being conducive to a rise in productivity. While our analysis here has been centered in eco-efficiency, it must not be forgotten that strong links can be discovered between eco-efficient scores and technical input/output efficiency scores.

Finally, we have shown that the eco-efficiency of individual farms, and also whole farming systems, could substantially differ concerning the management of particular environmental pressures from agricultural production. We hope that the use of some analytical tools in this paper (i.e. the directional distance function, and the ratio of metatechnology) may highlight their usefulness and help agricultural experts and authorities to focus their attention on the most demanding environmental problems in each particular case.

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Table 1. Sample description

	Conventional farms (96)		Ecological farms (98)		Equality of means t test	
	Mean	SD	Mean	SD	t test	p value
Economic performance						
Income (€ ha^{-1})	6325	3417	4573	3009	3.787	0.0002
Ecological performance						
Global Warming Potential (Kg CO2 eq. ha^{-1})	17853	9594	2285	1598	15.687	0.0000
Ozone Layer Depletion Potential (Kg R11 eq. ha^{-1})	994	547	32	18	17.244	0.0000
Eutrophication Potential (Kg PO_4^{3-} eq. ha^{-1})	56	26	63	59	-1.139	0.2568
Ecotoxicity (CTUeco ha^{-1})	663799	438024	270	535	14.842	0.0000
Human toxicity, carcinogen (CTUh 10^{-6} ha^{-1})	662	420	3	5	15.367	0.0000
Human toxicity, non-carcinogen (CTUh 10^{-6} ha^{-1})	2869	1607	125	81	16.708	0.0000

Table 2. Eco-efficiency indicators: Directional metadistance function (DMDF), directional distance function (DDF) and metatechnology ratio (MTR); averages.

	Conventional System			Ecological System		
	DMDF	DDF	MTR	DMDF	DDF	MTR
Reduction in all environmental impacts (Radial)	0.9089	0.5406	0.1993	0.5823	0.5823	1
Impact-specific indicators						
Reduction in environmental impacts of global nature	0.9720	0.6264	0.0803	0.6190	0.6190	1
Global warming potential	0.9720	0.6683	0.1043	0.7646	0.7646	1
Ozone depletion potential	0.9843	0.6420	0.0479	0.6451	0.6451	1
Reduction in environmental impacts of regional nature	0.9156	0.5554	0.1938	0.6838	0.6838	1
Eutrophication	0.9156	0.5868	0.2123	0.7788	0.7788	1
Ecotoxicity	0.9997	0.7491	0.0017	0.7488	0.7488	1
Reduction in human toxicity impacts	0.9922	0.6368	0.0232	0.6689	0.6689	1
Non-carcinogen	0.9922	0.6399	0.0234	0.7986	0.7986	1
Carcinogen	0.9981	0.7211	0.0089	0.6858	0.6858	1