Eco-efficiency in traditional rain-fed olive growing systems: A directional metadistance function approach.

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ABSTRACT: This paper assesses technological differences between traditional rain-fed olive growing systems in terms of their economic-ecological efficiency. In doing so, a sample of Spanish olive producers belonging to both traditional mountain and traditional plain growing systems is analysed. Directional distance functions are used to extend the non-parametric metafrontier approach by O'Donnell et al. (2008) to the assessment of technological differences in eco-efficiency between groups of producers at the level of specific environmental pressure management, which constitutes a methodological contribution of this paper. We find both olive growing systems to have great potential to reduce environmental pressures. Furthermore, the most eco-efficient technology is the traditional plain system in terms of pressures on natural resources, while the traditional mountain system is the most eco-efficient when considering pressures on biodiversity. These results might help policy makers design strategies that coincide to a greater extent with society preferences regarding the economic and ecological functions of agriculture.

KEYWORDS: Environmental pressures; Data Envelopment Analysis; metafrontier; directional distance function; agro environmental policy; Andalusia (Spain).

Environmental Economics

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1. Introduction

Modern agriculture is inherently multifunctional. Not only does it provide society with marketable goods such as food, fibre and fuel, but also exerts a profound impact on the environment as a biophysical activity. Some of those impacts are positive and represent ecosystem services and cultural benefits (Swinton et al., 2007), while others constitute costly and negative environmental externalities (Pretty, 2001). Here we are concerned with reducing negative environmental pressures at individual farm level, using the concept of economic-ecological efficiency.

In recent decades, economic-ecological efficiency, or simply eco-efficiency, has become increasingly popular as a way to assess the balance between economic performance and environmental degradation involved in economic activities (OECD, 1998; WBCSD, 2000). Eco-efficiency is commonly assessed at producer, industry or economy levels using ratios that relate the economic value of goods and services produced to the environmental pressures and impacts involved in production processes (Schmidheiny and Zorraquin, 1996). The fact that agriculture manages the largest amount of natural resources of all economic activities explains the practical relevance of assessing the economic and ecological efficiency of farm operations.

This paper assesses the eco-efficiency of traditional rain-fed olive growing systems in the Southern Spanish region of Andalusia, which is by far the main olive-producing area in the world. The relevance of the income and employment generated by olive farming in this region has been widely recognised (Gómez-Limón and Arriaza, 2011). However, this activity also exerts significant pressures on the environment, including soil erosion, loss of biodiversity and diffuse water pollution (Beaufoy and Pienkowski, 2000; EC, 2010; Gómez-Calero, 2009; Guzmán-Álvarez, 2005). Traditional Andalusian olive production is, nonetheless, far from homogeneous. In fact, it comprises several growing systems with fairly different topographical and climatic conditions and degrees of production intensification. These natural and technological differences heavily condition both economic and ecological performance.

Empirical studies undertaken to assess eco-efficiency in agriculture have mostly assumed that farms share the same production technology (De Koeijer et al., 2002; Picazo-Tadeo et al., 2011). However, this assumption is inappropriate when different groups of farms face different technological restrictions, as is the case of traditional rain-fed olive farming in Andalusia. Eco-efficiency under technological heterogeneity has been studied, at best, by estimating different technological frontiers for different groups of producers. However, this approach has the disadvantage that eco-efficiency scores are not directly comparable across groups because they are computed against different technological frontiers. The notion of a *metafrontier* representing an unrestricted technology helps to overcome this problem and permits the evaluation of technological heterogeneity among groups of producers as regards eco-efficiency.

Hayami and Ruttan (1970) defined the *metaproduction function* as the envelopment of all known technologies and assumed that only some of those technologies might be available to particular groups of producers. Battese and Rao (2002) and Battese et al. (2004) developed a stochastic metafrontier production function approach aimed at assessing technical efficiency and technological gaps between technologies belonging to different groups of producers. O'Donnell et al. (2008) approached the comparison of technical efficiency across groups of producers using non-parametric Data Envelopment Analysis (DEA) techniques. Some other papers have also used this approach, including Kontolaimou and Tsekouras (2010), Kounetas et al. (2009) and Sáez-Fernández et al. (2012).

Within this framework, the contribution of our paper is two-fold. On the one hand, we extend the metafrontier approach by O'Donnell et al. (2008) to analyse economic-ecological efficiency. Furthermore, using the recent work by Sáez-Fernández et al. (2012) and Picazo-Tadeo et al. (2012), eco-efficiency is assessed in terms of the management of specific environmental pressures or groups of pressures. In doing so, directional distance functions are employed. Consequently, our methodological approach detects technological differences that would have remained invisible to conventional metafrontier approaches based on the computation of radial or proportional measures of eco-efficiency. As far as the authors are aware, this has not been done before.

On the other hand, this methodological approach is used to assess technological differences at environmental pressure-specific level between traditional rain-fed olive growing systems in Andalusia (Southern Spain). The eco-efficiency of olive farming in this area has been studied in two recent papers.[1] Gómez-Limón et al. (2012) analyses the performance of olive growing systems using the program approach by Charnes et al. (1981) based on proportional measures of eco-efficiency. Furthermore, Picazo-Tadeo et al. (2012) uses directional distance functions to assess eco-efficiency at pres-

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[1] Furthermore, some papers have assessed efficiency in the olive sector in Andalusia, including Amores and Contreras (2009), who assessed technical efficiency in olive farming, and Dios-Palomares and Martínez-Paz (2011), who analysed technical, quality and environmental efficiency in the olive oil industry.

sure level in the traditional plain grove system. The contribution of this research, however, goes further than these two papers. Rather than providing an appraisal of farm performance regarding economic-environmental trade-offs, the paper contributes an assessment of the advantages and disadvantages of alternative olive growing systems as regards their eco-efficiency in the management of particular environmental pressures. In our opinion, this might provide policymakers with sound information to design agricultural policies that are more in sync with society priorities on the economic and ecological functions of olive production.

The paper proceeds as follows. Section 2 develops the methodology. Section 3 describes the characteristics of the olive farming systems studied and the data. Section 4 presents and discusses the results, while Section 5 concludes.

2. Methodology

2.1. Directional distance functions and metatechnology

Let us start by considering that we observe the economic performance of a set of k = 1,..., K farms, represented by value added v, and that their production processes cause a series of n = 1,..., N damaging pressures on the environment, which are also observed at farm level and denoted by the vector p = (p_1,..., p_n). Using previous research by Kuosmanen and Kortelainen (2005) (see also Picazo-Tadeo et al., 2012), the *pressure generating metatechnology set* (PGMT) representing all feasible combinations of value added and environmental pressures is defined as:

$$\mathrm{PGMT}=\left[(v,p)\in R_{+}^{1+N}\;\middle|\;\text{value added v can be generated with pressures p}\right] \qquad (1)$$

The metatechnology can also be represented by what is referred to here as the *pressure requirement metaset*, which represents all the combinations of environmental pressures that permit the generation of at least value added v, and is defined as:

$$\mathrm{PRMS}(v)=\left[p\;\middle|\;(v,p)\in \mathrm{PGMT}\right] \qquad (2)$$

Metatechnology is assumed to fulfil the following properties (Picazo-Tadeo et al., 2012): a) economic activity exerts some unavoidable pressures on the environment, such that the only way not to generate pressures is not to produce; b) it is always possible to generate a lower value added with the same environmental pressures; c) pressures can always be increased for any given value added; and finally, d) any convex combination of two or more observed pairs of value added and environmental pressures is also feasible. Accordingly, in line with previous papers by Korhonen and Luptacik (2004), Sarkis and Talluri (2004), Kuosmanen and Kortelainen (2005) and Zhang et al. (2008), environmental pressures are formally treated as conventional inputs.[2]

Let us now borrow the formal definition of eco-efficiency proposed by Kuosmanen and Kortelainen (2005) as a ratio between economic value added and an aggregate score of the pressure exerted on the environment by economic activity:

$$\mathrm{Eco-efficiency} = \frac{\text{Economic value added}}{\text{Environmental pressure}} = \frac{v}{F(p)}, \tag{3}$$

F representing the function that aggregates the n pressures exerted on the environment into a single pressure score.

According to the classification in Huppes and Ishikawa (2005), this is a micro-level environmental-productivity ratio approach, such that eco-efficiency improves when economic value added relative to aggregate environmental pressure increases. Furthermore, following the most common approach in this literature, the aggregate pressure score is obtained as a linearly weighted average of particular pressures, with weights w_n.[3] In formal terms:

$$F(p) = \sum_{n=1}^{N} w_n p_n \tag{4}$$

Adapting the *directional metadistance function* by Sáez-Fernández et al. (2012) to the context of our analysis of eco-efficiency yields:[4]

$$M\vec{D}\left[v, p; g = (g_v, -g_p)\right] = \mathrm{Sup}\left[\beta \,\middle|\, (p - \beta g_p) \in PRMS(v + \beta g_v)\right], \tag{5}$$

with the direction vector being

$$g = (g_v, -g_p) \tag{6}$$

The directional metadistance function in expression (5) is a very flexible tool for measuring eco-efficiency as it can assess simultaneous potential increases in value added and decreases in environmental pressures along a path previously defined by the researcher through a particular direction vector.

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[2] Dyckhoff and Allen (2001) and Seiford and Zhu (2002) discuss the advantages and disadvantages of different ways of dealing with the undesirable results of production processes in DEA-based models.

[3] Environmental pressures involved in the denominator of the eco-efficiency ratio are difficult to measure and aggregate due to the inexistence of market prices conveying unambiguous weights. While some studies have assigned external weights based on the opinion of experts, in this paper, as commented later on, eco-efficiency is assessed using DEA techniques that generate the weights of environmental pressures endogenously at farm level.

[4] The theory of directional distance functions (Chambers et al., 1996; Chambers et al., 1998) is summarised in Färe and Grosskopf (2000); Picazo-Tadeo et al. (2005) highlight its usefulness for environmental performance analysis.

Making use of this flexibility, let us assume that we are interested in evaluating the proportion by which all pressures exerted on the environment could be reduced without decreasing value added. The direction vector that models these preferences is:

$$g_{all} = (0, -p), \tag{7}$$

and the directional metadistance function becomes:

$$M\vec{D}_{all}\left[v, p; g_{all} = (0, -p)\right] = \text{Sup}\ \left[\beta_{all} \,\middle|\, (1-\beta_{all})p \in PRMS(v)\right] \tag{8}$$

The directional metadistance function in expression (8) is always equal to or greater than zero (Chambers et al., 1998), with a score of zero denoting eco-efficiency, i.e., no proportional reduction in environmental pressures is feasible without decreasing value added. Furthermore, it is upper-bounded to one, that is, the greater the metadistance function the lower the eco-efficiency.

We can also evaluate how much a given environmental pressure (or group of pressures) could be reduced without increasing the remaining pressures and maintaining value added at its observed level. Following Picazo-Tadeo et al. (2012), i being the pressure (or group of pressures) to be reduced and –i the remaining pressures, the direction vector that models this schedule of preferences is:

$$g_i = \left[0, (-p_i, 0)\right], \tag{9}$$

and the directional metadistance function:

$$M\vec{D}_i\left[v, p; g_i = \left(0, \langle -p_i, 0\rangle\right)\right] = \text{Sup}\ \left[\beta_i \,\middle|\, \langle (1-\beta_i)p_i, p_{-i}\rangle \in PRMS(v)\right], \tag{10}$$

2.2. Group frontiers

Following O'Donnell et al. (2008), let us now consider that farms in our sample are split into several groups so that constraints imposed by the production environment prevent producers belonging to certain groups from accessing the full range of combinations between value added and environmental pressures in the metatechnology. The *pressure generating technology set* for group h, representing all combinations of value added and environmental pressures available to farms in that group is:

$$PGT^h = \left[(v, p) \in R_+^{1+N} \,\middle|\, \begin{array}{l}\text{value added v can be} \\ \text{generated by farms in group h with pressures p}\end{array}\right], \tag{11}$$

and the *pressure requirement set* for that group h:

$$PRS^h(v) = \left[p \,\middle|\, (v, p) \in PGT^h\right] \tag{12}$$

Furthermore, we assume that the technology of each group h satisfies the same properties as the metatechnology, including convexity.

Directional distance functions can also be used to evaluate the eco-efficiency of farms in group h against the pressure generating technology of their own group. Accordingly, the functions that assess the potential to reduce all environmental pressures proportionally and the potential to reduce a pressure or group of pressures i with respect to the technology of group h, in both cases keeping value added at the observed level, are respectively:

$$\vec{D}^{h}_{all}\left[v,p;\, g_{all}=\left(0,-p\right)\right]=\text{Sup}\,\left[\beta^{h}_{all}\ \middle|\left(1-\beta^{h}_{all}\right)p\in PRS^{h}\left(v\right)\right], \tag{13}$$

and

$$\vec{D}^{h}_{i}\left[v,p;\, g_{i}=\left(0,\left\langle -p_{i},0\right\rangle\right)\right]=\text{Sup}\,\left[\beta^{h}_{i}\ \middle|\left\langle\left(1-\beta^{h}_{i}\right)p_{i},p_{-i}\right\rangle\in PRS^{h}\left(v\right)\right] \tag{14}$$

The directional distance functions computed with respect to the technology of group h are, by construction, equal to or lower than the directional metadistance functions computed relative to the metatechnology.

2.3. Eco-efficiency and metatechnology ratios

O´Donnell et al. (2008) used conventional Shephard’s distance functions to compute scores of radial or proportional technical efficiency with respect to both a metatechnology set and the technologies of different groups of producers. These scores are then used to define the so-called *metatechnology ratio*, which assesses how close the technology of group h is to the metatechnology. As already noted, in this paper we use recent research by Sáez-Fernández et al. (2012) and Picazo-Tadeo et al. (2012) to extend the approach by O’Donnell and colleagues to assess eco-efficiency, but also, and more noticeably, to calculate metatechnology ratios in directions other than proportional reductions in all environmental pressures.

In order to compute our metatechnology ratios, it is strongly advisable to express the directional metadistance and distance functions more conventionally.[5] Let us then define the following measures of eco-efficiency for farm k belonging to group h relative, respectively, to the metatechnology and the technology of group h, in the scenario in which all environmental pressures are proportionally reduced:

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[5] The reason is that, as defined by O’Donnell et al. (2008), metatechnology ratios involving eco-efficient farms could not be defined as directional distances due to these observations being equal to zero.

$$\text{Metaeco}-\text{efficiency}^{k}_{all}=\left[1-M\vec{D}^{k}_{all}\left\langle v^{k},p^{k};\, g_{all}=\left(0,-p^{k}\right)\right\rangle\right]=\left(1-\beta^{k}_{all}\right), \tag{15}$$

and

$$\text{Eco}-\text{efficiency}^{hk}_{all}=\left[1-\vec{D}^{hk}_{all}\left\langle v^{k},p^{k};\, g_{all}=\left(0,-p^{k}\right)\right\rangle\right]=\left(1-\beta^{hk}_{all}\right) \tag{16}$$

The relationship between metadistance/distance functions and the measures of eco-efficiency defined in (15) and (16) is straightforward. For example, a metadistance function of, say, 0.2 means that farm k could reduce all its environmental pressures by 20% while maintaining value added; however, it also means that the same value added could be generated with only 80% of the pressures actually exerted on the environment, which is just what expression (15) quantifies, i.e., the metaeco-efficiency score is 0.8. This measure of eco-efficiency is upper-bounded to one, which represents full eco-efficiency; moreover, the lower the score the lower eco-efficiency. Furthermore, the eco-efficiency computed relative to the technology of group h will always be equal to or higher than the metaeco-efficiency computed relative to the metatechnology, which is a way of saying that the metafrontier envelops the frontier of group h.

Let us now define the *metatechnology ratio* for farm k in group h as:

$$\text{Metatechnology ratio}^{hk}_{all}\left[v^{k},p^{k};\, g_{all}=\left(0,-p^{k}\right)\right]=\frac{\text{Metaeco}-\text{efficiency}^{k}_{all}}{\text{Eco}-\text{efficiency}^{hk}_{all}}=\frac{\left(1-\beta^{k}_{all}\right)}{\left(1-\beta^{hk}_{all}\right)} \tag{17}$$

Metatechnology ratios reveal how close the technology of group h is to the metatechnology, assessed in a direction that reduces all environmental pressures in the same proportion and maintains observed levels of value added. Going back to the example above, let us assume that the eco-efficiency score for farm k relative to the technology of group h is 0.85. Thus, the metatechnology ratio is 0.94, indicating that the eco-efficient level of environmental pressures of farm k relative to the metafrontier is 94% of the eco-efficient level with respect to the technology of group h.

Adapting the reasoning in O'Donnell *et al.* (2008: 237), this approach provides a useful breakdown of a measure of eco-efficiency defined with respect to the metatechnology, referred to here as *metaeco-efficiency*, into the product of a measure of eco-efficiency relative to the technology of group h, constrained by the production environment, and the metatechnology ratio for that group, which measures the gap between the technology of group h and the metatechnology. Formally for farm k:

$$\text{Metaeco}-\text{efficiency}^{k}_{all}=\text{Eco}-\text{efficiency}^{hk}_{all}\times\text{Metatechnology ratio}^{hk}_{all} \tag{18}$$

Similarly, metatechnology ratios can be computed using a direction vector that contracts only one environmental pressure or group of pressures i, while maintaining the remaining pressures and value added. In this case, transforming our metadistance and distance functions into measures of eco-efficiency yields:

$$\text{Metaeco}-\text{efficiency}_i^k=\left\{1-M\vec{D}_i^k\left[v^k,p^k;\,g_i=\left(0,\left\langle -p_i^k,0\right\rangle\right)\right]\right\}=\left(1-\beta_i^k\right), \tag{19}$$

and

$$\text{Eco}-\text{efficiency}_i^{hk}=\left\{1-\vec{D}_i^{hk}\left[v^k,p^k;\,g_i=\left(0,\left\langle -p_i^k,0\right\rangle\right)\right]\right\}=\left(1-\beta_i^{hk}\right) \tag{20}$$

Accordingly, the pressure-specific *metatechnology ratio* for farm k of group h and environmental pressure or group of pressures i is computed as:

$$\text{Metatechnology ratio}_i^{hk}\left[v^k,p^k;\,g_i=\left(0,\left\langle -p_i^k,0\right\rangle\right)\right]=\frac{\text{Metaeco}-\text{efficiency}_i^k}{\text{Eco}-\text{efficiency}_i^{hk}}=\frac{\left(1-\beta_i^k\right)}{\left(1-\beta_i^{hk}\right)} \tag{21}$$

The difference between this metatechnology ratio and that in expression (17) is that eco-efficiency is now assessed with a direction that reduces environmental pressure or group of pressures i without increasing the remaining –i pressures and maintaining value added. The aforementioned decomposition of eco-efficiency holds.

Let us finally provide a graphic illustration of our metatechnology ratios. In order to do so, we assume a technology that generates a value added v with two pressures on the environment, namely p_1 and p_2. Furthermore, we observe farms A to F, in addition to farm J; observations A, B and C are represented by dots and belong to group 1, and farms D, E, F and J, identified by crosses, belong to group 2. Under the assumptions made regarding the pressure generating technology, the technological frontier for group 1 is defined by eco-efficient farms A, B and C and their convex combinations, while the segment DEF shapes the eco-efficient technological frontier of the farms in group 2. The metatechnology is a convex combination of the technologies of both groups and is shaped by observations A and B, belonging to group 1, and F, to group 2.

Farm J is unambiguously eco-inefficient as it exerts more environmental pressures than strictly necessary to generate one unit of value added according to both the technology of the group it belongs to and to the metatechnology. Projecting farm J onto the technological frontier of group 2 with a direction vector that proportionally reduces p_1 and p_2 yields point J_1, while projecting it onto the metatechnology yields point J_2. The metatechnology ratio of expression (17) would measure the technological gap that exists between the technology of group 2 and the metatechnology. This reasoning can be easily extrapolated to measure the technological gap in a direction that only reduces pressure p_2 while maintaining p_1 and value added; in this scenario, projecting DMU J onto the technology of group 2 and onto the metatechnology will yield, respectively, points J_3 and J_4. The difference in regard to the scenario where all pressures are proportionally reduced is that we are now assessing the technological gap that exists between the technology of group 2 and the metatechnology in the management of specific environmental pressure p_2.

2.4. Computing directional metadistance and distance functions

The metadistance and distance functions involved in our metatechnology ratios are computed using well-known Data Envelopment Analysis techniques (DEA) (Cooper et al., 2007). Accordingly, the programs required to compute the directional metadistance functions for farm k’ in expressions (8), in which all environmental pressures are reduced, and (10), where only environmental pressure or group of pressures i is reduced, are respectively:

$$
\begin{array}{llll}
\multicolumn{4}{l}{\text{Maximize}_{\beta^{k'}_{all},\, z^k}\ \beta^{k'}_{all}} \\
\multicolumn{4}{l}{\text{subject to:}} \\
\quad v^{k'} \leq \sum_{k=1}^{K} z^k v^k & & \text{(i)}\ , & \\
\quad \left(1-\beta^{k'}_{all}\right) p^{k'}_n \geq \sum_{k=1}^{K} z^k p^k_n & n=1,\dots,N & \text{(ii)} & \qquad (22) \\
\quad z^k \geq 0 & k=1,\dots,K & \text{(iii)} &
\end{array}
$$

and

$$
\begin{array}{llll}
\multicolumn{4}{l}{\text{Maximize}_{\beta^{k'}_{i},\, z^k}\ \beta^{k'}_{i}} \\
\multicolumn{4}{l}{\text{subject to:}} \\
\quad v^{k'} \leq \sum_{k=1}^{K} z^k v^k & & \text{(i)} & \\
\quad \left(1-\beta^{k'}_{i}\right) p^{k'}_i \geq \sum_{k=1}^{K} z^k p^k_i & i \in n \text{ and } i \notin -i & \text{(ii)} & \qquad (23) \\
\quad p^{k'}_{-i} \geq \sum_{k=1}^{K} z^k p^k_{-i} & -i \in n & \text{(iii)} & \\
\quad z^k \geq 0 & k=1,\dots,K & \text{(iv)} &
\end{array}
$$

z^k representing the weighting of each farm k in the construction of the metaeco-efficient frontier.[6]

As the basic distinction between metadistance and group distance functions has already been established, here we only present the programs required to compute the metadistance functions; minimal changes in notation and the use of only the farms in

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[6] In order to compute directional metadistance and distance functions we have used the so-called dual approach; the weights of the specific environmental pressures involved in the denominator of the single environmental pressure in expression (3) can be directly obtained from the primal approach.

group h are necessary to compute the group directional distance functions in expressions (13) and (14).

3. Olive farming systems: variables and data set

3.1. Case study

We use a sample of olive farms located in the Southern Spanish region of Andalusia which is by far the greatest olive producer worldwide, representing 19% of the surface area devoted to olive growing in the entire world. Moreover, olive production occupies around one third of the surface area used for agricultural purposes in the region and generates important economic, environmental and social effects (Gómez-Limón and Arriaza, 2011). However, as mentioned in the Introduction, olive growing in this area is far from homogeneous and different natural conditions and technology result in quite different olive farming systems.

Here, we focus on the two traditional rain-fed olive farming systems in Andalusia, which jointly account for around two thirds of the olive surface area in this region:

(i) *Traditional mountain groves*, covering 444,465 hectares (32.7% of olive surface area in Andalusia) are run on high sloped land and in rain-fed conditions with a low density of trees per hectare. Furthermore, plantations make little use of agrochemicals, but do use a large amount of labour.

(ii) *Traditional plain groves*, which occupy 436,942 hectares (32.1% of olive surface area), are characterised by moderately sloped land, rain-fed conditions and also a low density of trees per hectare.

Olive growing systems have been considered historically as *High Nature Value* (NHV) farmland, since agricultural systems featured as low-input plantations with valued biodiversity and landscape and positive effects on soil and water management (Beaufoy and Pienkowski, 2000; EEA, 2004). These agricultural systems were also characterised by poor economic performance and hence vulnerable to abandonment. However, from the 1980s onward, these systems have evolved by taking advantage of the favourable policy scenario provided by European Common Agricultural Policy (CAP), intensifying their production technology by means of increasing the number of trees per hectare, using mechanised tillage and herbicides to control weeds and applying a substantial amount of fertilisers and pesticides. These changes considerably improved the economic performance of olive farming in Andalusia while also markedly worsening its ecological balance.

3.2. Variables

Economic performance

Economic performance is assessed by total value added per hectare and year (TVA)[7], which represents the ability of olive farms to generate income, including land, capital and labour income. Some authors have used alternative measures of economic performance in olive farming, such as net income, arguing that value added does not compute labour as a cost. In fact, labour is the most important cost in this activity, accounting for around 60% of total costs. However, besides being an important production cost, labour is also an essential source of income for farmers and their families, as more than 70% of the labour employed in olive-growing is family labour. As total value added includes land and capital, but also labour incomes, it constitutes, in our opinion, a better proxy for economic performance than net income from the perspective of the sustainability of olive farming.

In practice, total value added has been computed at farm level by subtracting direct costs, including fertilisers, pesticides, energy, services outsourced and depreciation and maintenance of facilities, from the income obtained from the sale of olives (both measured annually in € at 2010 prices). Formally for farm k:

$$\mathrm{TVA}^k = v^k = \frac{\mathrm{Sales}^k - \mathrm{Direct\ costs}^k}{\mathrm{Land}^k} \tag{24}$$

Obviously, the higher the total value added, the better the economic performance.

Ecological performance

In order to assess ecological performance, we have considered two types of environmental pressures, namely, pressures on natural resources and pressures on biodiversity. Regarding pressures on natural resources, it is worth emphasizing soil erosion as one of the main environmental problems linked to olive farming. Erosion reduces soil fertility and pollutes water resources, the latter being particularly noticeable when vulnerable land is subjected to poor farming practices (Gómez-Calero et al., 2003; Vanwalleghem et al., 2010). Similarly, the mechanisation and intensification of traditional olive farming in Andalusia has increased energy requirements (EC, 2010). This study employs two variables to capture the pressure that olive farming exerts on natural resources, namely erosion and energy use.

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[7] This indicator excludes as a source of income the payments received by olive-growers from the *Common Agricultural Policy* (CAP), as they are currently decoupled from production and also delinked from the provision of particular environmental services.

The pressures of farming on biodiversity include aspects such as wildlife conservation, habitat protection and creation, maintenance of crop genetic diversity and the utilisation of natural biological processes in production procedures. The pressures that olive farming exerts on biodiversity depend on factors such as the use of pesticides, weed control methods and frequency, the presence of scrub and/or woodland and the age of trees (Beaufoy and Pienkowski, 2000; Duarte et al., 2009). In relation to these pressures, we use two indicators linked to the effect of farming practices on biodiversity and the use of pesticides, respectively.

Formally, the four environmental pressures considered in this study have been calculated for each olive grove as described below.

Erosion. This variable measures the amount of eroded land on each farm (tonnes per hectare and year) as a result of farm soil management and is calculated as the difference between actual erosion and the erosion that would occur in natural conditions, referred to here as erosion of reference, equivalent to the erosion that soil would suffer if it were covered by Mediterranean woodland. The computation for each farm k is based on the revised universal equation of soil loss (Renard et al., 1997):

$$\begin{aligned}\text{Erosion}^k &= \text{Actual erosion}^k - \text{Erosion of reference}^k = \\ &\left(R^k \cdot K^k \cdot LS^k \cdot C^k \cdot P^k\right) - \left(R^k \cdot K^k \cdot LS^k\right)\end{aligned} \qquad (25)$$

The influence of natural factors on erosion is captured by rainfall intensity (R^k), soil hardness (K^k) and the slope and length of the farm slope (LS^k), whereas the influence of land cover practices and the type of tillage used is captured by terms C^k and P^k, respectively (see details in Gómez-Calero et al., 2003). All these elements have been calculated at farm level.

Energy. Farming plays an important environmental role in regard to climate change (Foley et al., 2005). Olive production consumes energy, thus contributing to carbon dioxide (CO_2) emissions, but also fixes energy through photosynthesis, which is accumulated in outputs, thus absorbing CO_2.[8] The variable *energy* is intended to account for this relationship and is computed for farm k as:

$$\text{Energy}_k = \frac{365}{\sum_{o=1}^{O} \text{Energy in output}_{ok} - \sum_{q=1}^{Q} \text{Energy in input}_{qk}} \qquad (26)$$

The denominator assesses the energy balance as the difference between the energy fixed by olive groves in outputs (variable o) and the energy included in the inputs

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[8] Lal (2004) and Smith et al. (2008) review the literature on the impact of farming on climate change.

used in the production process (variable q), both measured in gigajoules (GJ) per hectare and year. Accordingly, this expression measures the number of days required for each hectare belonging to farm k to generate 1 GJ of net energy (see details in Picazo-Tadeo et al., 2012).

Biodiversity. The pressure exerted by olive farming on biodiversity is measured by an *ad hoc* composite indicator accounting for several agricultural practices, including maintaining vegetal covers on soil (*cover*), controlling vegetal covers by sheep/horse (*grazing*), piling up pruning residues (*piling*) and allowing some olives to remain on trees after the harvest (*olives*). These categorical variables take a value of zero if the agricultural practices that enhance biodiversity are actually put into practice and one if they are not; the only exception is the variable *cover*, which measures the proportion of days in a year that the soil does not have a vegetal cover. The weights assigned to each agricultural practice come from the evaluation of a panel of ten experts in ecology and olive farming agronomy (see Gómez-Limón and Arriaza, 2011). This indicator ranges between zero and one and is formally computed for farm k as:

$$\begin{aligned}\text{Biodiversity}_k &= 0.636\ \text{Cover}_k + 0.108\ \text{Grazing}_k + 0.146\ \text{Piling}_k \\ &+ 0.110\ \text{Olives}_k\end{aligned} \tag{27}$$

Pesticide risk. This variable is also related to biodiversity and quantifies the overall toxicity released into the environment by the pesticides used for olive production. This toxicity has been estimated in terms of how potentially lethal the active matters contained in those agrochemicals are for live organisms, considering lethal doses 50%[9] (for further details see Gómez-Limón et al., 2012). This is measured in kilograms of rat per hectare and year. Formally:

$$\text{Pesticide risk}_k = \sum_{m=1}^{M} 1{,}000 \frac{\text{Active matter in commercial product}_{mk}}{\text{Lethal dose 50\%}_m} \tag{28}$$

In all cases, the higher the value of the variable representing the pressure exerted by farm k on the environment, the poorer its ecological performance.

3.3. Data gathering

The information used to calculate the variables defined in Section 3.2 comes from a survey. These data have been completed using secondary information valid for all farms in the sample from two main sources, namely, the scientific literature on technical coefficients valid worldwide required to compute environmental pressures (e.g.,

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[9] The 50% lethal dose is the quantity of product required to kill half the members of a population of rats and is measured in grams per kilogram of rat.

energy contained per unit of input used in olive farming or the active matters contained in the agrochemicals used) and official statistics for input and output prices required to calculate total value added (see Gómez-Limón and Arriaza, 2011 and Gómez-Limón et al., 2012 for further details). Our sample includes 220 olive farms, 99 of which belong to the traditional mountain system, while the remaining 121 belong to the traditional plain system.

Table 1 displays some descriptive statistics for the sample. According to the results from the Mann-Whitney test, the indicators of economic performance are not significantly different across farming systems at standard confidence levels. Regarding ecological performance, there are significant differences between systems. The traditional mountain system performs very poorly in regard to erosion, but records favourable results in terms of biodiversity and pesticide risk. In contrast, erosion is less relevant in the traditional plain system, while the extent of pressures on biodiversity is more important.

4. Results and discussion.

Using the methodology developed in Section 2, we have calculated, in the first place, the metadistances of expressions (8) and (10) with respect to the metatechnology for each farm k in the sample described in Section 3. In the second place, we have computed the distances of expressions (13) and (14) also for each farm k with respect to the technology in their own group or production system. In order to do so, we have considered a series of direction vectors modelling scenarios that represent different objectives in regard to environmental pressure reduction. Apart from a scenario in which all pressures are proportionally reduced, six additional scenarios with specific objectives have been considered. Four of them aim to ascertain the maximum reduction in each individual environmental pressure, while the other two seek the maximum proportional reduction in the pressures exerted on natural resources (erosion and energy) and biodiversity (biodiversity and pesticide risk), respectively. In all cases, the reduction in environmental pressures is subject to the condition of maintaining value added at observed levels without increasing the rest of pressures. Table 2 presents the results.

4.1. Eco-efficiency by olive system

In the first place, let us briefly analyse the results obtained concerning potential savings in pressures within each olive growing system using the directional distance functions (DDF) reported in the third column of Table 2. When compared to the best practices in their own group, traditional mountain farms could, on average, proportionally reduce the environmental pressures they exert by 45.1%, while maintaining their value added. This potential saving is much higher when the objective is to reduce only the pressures on natural resources (55.2%) or biodiversity (51.6%), while maintaining the rest of pressures and economic performance. The enormous potential to reduce erosion is also striking (73.8%). In traditional plain olive groves, the potential for proportional savings in all pressures averages 49.3%, with the potential to reduce the pressure on natural resources figuring prominently (64.3%), particularly where erosion is concerned (80.3%). In this system pressures on biodiversity can be reduced by 55.2%.

It is very important to stress, nonetheless, that the eco-efficiency results for traditional mountain and traditional plain groves commented above are in no way directly compared. The reason is that efficiency is a *relative* concept measured with respect to a given benchmark or technological frontier, and the eco-efficiency of the farms in our sample has been assessed in regard to two different technological frontiers that represent, respectively, the best observed practices within each olive-growing system. The only sensible comment that can be made regarding these results is that traditional mountain groves are, on average, closer to their own technological frontier than the farms that belong to the traditional plain system.

4.2. Do technologies really differ from one olive growing system to another?

In order to ascertain the technological differences between systems, we have calculated the metatechnology ratios (MTR) of expressions (17) and (21), which are presented in the last column of Table 2.[10] It is worth recalling here that the metatechnology ratio measures the proportion between the eco-efficient level of pressures in regard to the metatechnology and the eco-efficient pressures achievable with the technology available to a given olive grove system. In order to rank our two traditional olive-growing systems according to their eco-efficiency in each scenario of environmental pressure reduction, we have compared their metatechnology ratios. In particular, the statistical significance of the differences between both metatechnology ratios has been assessed using the Mann and Whitney test. The results are in Table 3.

In the scenario where the objective is to proportionally reduce all environmental pressures while maintaining value added, the technological frontier of the traditional plain system is closest to the metafrontier; that is, it is the system with the most eco-

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[10] Beforehand, the Wilcoxon signed rank sum test was used to compare the potential savings in pressures in regard to the technology of each group (DDF) to the potential savings in regard to the metatechnology (DMDF). The results show that there are significant differences between the two and, therefore, thereby justifying the analysis of the metatechnology ratio.

efficient technology.[11] The difference, moreover, is statistically significant at a confidence level of 1%. If the olive groves in this system had access to the metatechnology, they could obtain the same value added while generating on average 97.7% of the pressures they would generate using the best practices available to their group, that is, their metatechnology ratio is 0.977. The technological differences between the traditional mountain system and the metafrontier are greater, with a metatechnology ratio of 0.923.

The system ranking changes substantially in alternative scenarios where the objective is to reduce one environmental pressure or group of pressures while maintaining the rest of pressures and economic performance, which highlights the relevance of the methodological approach employed in this study. As regards the pressures exerted by olive growing on natural resources, the traditional plain system has by far the most eco-efficient technology; the metatechnology ratios are, respectively, 0.989 and 0.563 for traditional plain and traditional mountain groves, the difference being statistically significant. This ranking is maintained where the individual pressures erosion and energy are concerned, providing evidence of the adverse effect of the natural and technological conditions of mountain olive groves on eco-efficiency, particularly in regard to erosion.

As regards the pressures exerted on biodiversity, with a metatechnology ratio of 0.981, the technology of traditional mountain olive groves is more eco-efficient than the technology of the traditional plain system, where the metatechnology ratio is 0.928; moreover, the difference is statistically significant. This result also remains unchanged in regard to particular pressures on biodiversity and pesticide risk, indicating the disadvantages of the natural and technological conditions of traditional plain groves where the management of pressures on biodiversity is concerned. Nevertheless, it is worth indicating that the restrictions imposed by technology on the eco-efficient management of pressures exerted on biodiversity are less important in quantitative terms than those imposed on the management of natural resources. On average, in the case of pressures on biodiversity, access to the metatechnology would improve eco-efficiency, depending on the scenario, by between 3 and 6 points. However, the limitations imposed by the production environment on the eco-efficient management of pressures related to natural resources are certainly relevant in the case of the mountain olive grove system, with differences of up to 44 points.

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[11] Using a methodology based on the concept of program efficiency by Charnes et al. (1981), Gómez-Limón et al. (2012) reach the same conclusion.

5. Summary, policy implications and further extensions

Increasing concern over the environmental implications of farming makes information on the relationships between agriculture and the environment a key aspect of designing and implementing agricultural policy. This paper analyses the economic-ecological efficiency of two olive growing systems in Spain, namely traditional mountain olive groves and traditional plain olive groves. In order to do so, directional distance functions are employed to adapt the metafrontier approach by O'Donnell et al. (2008) to the analysis of eco-efficiency at specific environmental pressure level. This approach is in itself a methodological contribution to this field of research, as it detects technological differences that would have remained hidden using conventional approaches based on proportional measures of efficiency. For example, a group of producers might well enjoy a technological advantage in the management of one environmental pressure, but be disadvantaged in the management of other pressures.

As regards the eco-efficiency scores of each olive grove system, the huge potential to reduce environmental pressures without affecting economic performance is striking. In both systems, the most relevant improvements could be achieved in the pressures on natural resources and erosion in particular. In relation to the technological differences between systems, the production technology used in the traditional plain system is more eco-efficient in a general scenario that contemplates reductions in all environmental pressures and also when only the pressures on natural resources are considered. However, this system has the least eco-efficient technology in relation to the pressures exerted by olive growing on biodiversity, where the technological superiority of the traditional mountain system stands out. It is also worth highlighting that the technological differences between systems regarding the pressures on biodiversity are quantitatively less relevant than the differences recorded in the case of the pressures on natural resources.

These results could be relevant in our opinion when it comes to designing agricultural policies more in keeping with the objectives of policymakers and society in general, in relation to the economic and environmental functions that olive groves should perform. On the one hand, policymakers must be aware of just how eco-inefficient the production systems studied are and the potential that exists to reduce environmental pressures without incurring any cost whatsoever in terms of the economic performance of olive farms. In this sense, it would be necessary to take steps to promote eco-efficiency based mainly on farmer training and support for the implementation of more sustainable technologies (Xiloyannis et al., 2008).

On the other hand, it is also important that agricultural policymakers are aware of the fact that actions aimed at promoting one productive system in particular can help to mitigate certain environmental pressures, but seriously damage the environment where other pressures are concerned. By way of example, a policy aimed at maintaining mountain olive groves in Andalusia would favour biodiversity, but would tend to aggravate the pressure on natural resources, particularly erosion. In this sense, a recent paper by Duarte et al. (2008) advocates for the implementation of subsidies for mountain olive growing on the basis of its agro environmental benefits. However, the results of our study reveal that when considering the economic and ecological performance of olive groves simultaneously, the traditional mountain system has the least favourable technology in terms of natural resource management.

Finally, we would like to highlight certain limitations that should be taken into account when interpreting our results, together with future avenues for research. In the first place, we must say that the indicators calculated in this study do not measure the absolute ecological performance of the farms or agricultural systems analysed, but rather their ecological performance in relation to economic performance. In the second place, the results referring to the reduction in environmental pressures must also be understood in relative terms, as absolute reductions in pressures would be different in two farms or productive systems with the same eco-efficiency if they initially exert different levels of pressure on the environment. Both these circumstances should be taken into account when designing agricultural policies if the objective of policymakers is to reduce the absolute pressure exerted by olive growing on the environment in order to boost sustainability. Indeed, an improvement in eco-efficiency does not necessarily guarantee an improvement in system sustainability, as the latter concept demands taking into account the absolute value of pressures and the capacity of the ecosystem to absorb them. In the third place, and as a possible extension to our study, it would be interesting to assess the technological differences between olive growing systems in alternative scenarios in which potential improvements in the economic performance of farms were considered.

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Table 1. Sample description

	All farms (220)		Traditional mountain groves (99)		Traditional plain groves (121)		Mann-Whitney test	
	Mean	SD	Mean	SD	Mean	SD	z-statistic	p-value
Economic performance								
Total Value Added (€/ha/year)	1,505	616	1,408	460	1,583	710	-1.157	0.247
Ecological performance								
Erosion (tons/ha/year)	10.34	9.14	16.27	9.72	5.49	4.74	9.616	0.000
Energy (days/GJ/ha)	14.22	12.89	13.51	8.54	14.80	15.58	0.765	0.444
Biodiversity (non-dimensional)	0.62	0.24	0.47	0.20	0.75	0.19	-8.144	0.000
Pesticides (kg of rat/ha/year)	4,451	3,816	3,443	2,648	5,276	4,397	-4.516	0.000

Table 2. Directional metadistance functions (DMDF), directional distance functions (DDF) and metatechnology ratios[a] (MTR); averages.

	TRADITIONAL MOUNTAIN GROVES		
	DMDF	DDF	MTR
All environmental pressures (radial)	*0.495*	*0.451*	*0.923*
Pressures on natural resources	*0.719*	*0.552*	*0.563*
Erosion	0.903	0.738	0.199
Energy	0.720	0.579	0.609
Pressures on biodiversity	*0.530*	*0.516*	*0.981*
Biodiversity	0.605	0.583	0.970
Pesticide risk	0.656	0.645	0.985

	TRADITIONAL PLAIN GROVES		
	DMDF	DDF	MTR
All environmental pressures (radial)	*0.502*	*0.493*	*0.977*
Pressures on natural resources	*0.654*	*0.643*	*0.989*
Erosion	0.816	0.803	0.987
Energy	0.682	0.670	0.988
Pressures on biodiversity	*0.576*	*0.552*	*0.928*
Biodiversity	0.679	0.656	0.937
Pesticide risk	0.659	0.639	0.925

[a] The metatechnology ratios are computed using the metaeco-efficiency/eco-efficiency measures defined in expressions (15), (16), (19) and (20), instead of the distance/metadistance functions directly.

Table 3. Differences in the metatechnology ratio

	Mann-Whitney test z-statistic	 p-value	Ranking from more to less eco-efficient
All environmental pressures (radial)	*-5.42*	*0.000*	*TRADITIONAL PLAIN > TRADITIONAL MOUNTAIN*
Pressures on natural resources	*-12.958*	*0.000*	*TRADITIONAL PLAIN > TRADITIONAL MOUNTAIN*
Erosion	-13.155	0.000	TRADITIONAL PLAIN > TRADITIONAL MOUNTAIN
Energy	-129.461	0.000	TRADITIONAL PLAIN > TRADITIONAL MOUNTAIN
Pressures on biodiversity	*7.874*	*0.000*	*TRADITIONAL MOUNTAIN > TRADITIONAL PLAIN*
Biodiversity	7.241	0.000	TRADITIONAL MOUNTAIN > TRADITIONAL PLAIN
Pesticide risk	9.782	0.000	TRADITIONAL MOUNTAIN > TRADITIONAL PLAIN

Figure 1. Eco-efficiency and metafrontier ratios