Environmental Impact Assessment Review 63 (2017) 116–127

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Assessing eco-efficiency: A metafrontier directional distance function approach using life cycle analysis

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A R T I C L E   I N F O

Article history:
Received 8 March 2016
Received in revised form 4 October 2016
Accepted 3 January 2017
Available online xxxx

Keywords:
Data envelopment analysis
Directional distance function
Eco-efficiency
Life cycle analysis
Metafrontier
Organic citrus farming

A B S T R A C T

Sustainability analysis requires a joint assessment of environmental, social and economic aspects of production processes. Here we propose the use of Life Cycle Analysis (LCA), a metafrontier (MF) directional distance function (DDF) approach, and Data Envelopment Analysis (DEA), to assess technological and managerial differences in eco-efficiency between production systems. We use LCA to compute six environmental and health impacts associated with the production processes of nearly 200 Spanish citrus farms belonging to organic and conventional farming systems. DEA is then employed to obtain joint economic-environmental farm's scores that we refer to as eco-efficiency. DDF allows us to determine farms' global eco-efficiency scores, as well as eco-efficiency scores with respect to specific environmental impacts. Furthermore, the use of an MF helps us to disentangle technological and managerial eco-inefficiencies by comparing the eco-efficiency of both farming systems with regards to a common benchmark. Our core results suggest that the shift from conventional to organic farming technology would allow a potential reduction in environmental impacts of 80% without resulting in any decline in economic performance. In contrast, as regards farmers' managerial capacities, both systems display quite similar mean scores.

1. Introduction

Modern agricultural systems can be considered as ecosystems whose properties have been amended in some way to increase productivity (Pretty, 2008), thus providing food and fibre to a rapidly growing human population. The relationship between agricultural systems and natural ecosystems covers a wide range of positive and negative effects (Power, 2010; Swinton et al., 2007; Zhang et al., 2007), and a variety of frameworks have been developed to explore the links between farming and the environment (EEA, 2005; EEA, 2006; OECD, 1993, 1999a, 1999b, 2001; Rao and Rogers, 2006; Smyth and Dumanski, 1993; van Cauwenbergh et al., 2007). It is within this context that the term 'agricultural sustainability' has been coined, relating to the concern about the potential negative consequences of modern farming, such as the depletion or degradation of natural resources. Nevertheless, as shown by its wide range of alternative meanings, sustainability is something of 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. One is based on the identification of management strategies deemed sustainable (e.g. organic agriculture), and the other on achieving a targeted state of the agro-system defined as sustainable and evaluated with a set of indicators. Nowadays, organic farming systems are widely regarded as 'sustainable' by the general public, or at least as relatively more 'sustainable' than conventional ones. Promoting organic farming may pave the way for a sustainable agriculture. The advantages of organic systems over conventional systems with respect to the conservation of natural resources and the reduction of environmental impacts per unit area have been demonstrated by several meta-analyses of research carried out on a global (Mondelaers et al., 2009) and European scale (Tuomisto et al., 2012), though there is a wide range of impact variation between different impact categories within both types of farming systems. Nevertheless, inferior yields per hectare and reduced 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 (Beltrán-Esteve and Reig-Martínez, 2014; De Ponti et al., 2012; Offermann and Nieberg, 2000). Therefore, it is of paramount importance on both scientific and

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http://dx.doi.org/10.1016/j.eiar.2017.01.001
0195-9255/

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 establish a sound basis for a comprehensive comparison of the two 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 perform this comparison (Govindan et al., 2014; Zhu et al., 2014).

According to the OECD (1998, p. 7), 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".

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 broader notion of sustainability, but it must be recognized 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 impacts, 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 cost savings, while simultaneously reducing environmental impacts (Ekins, 2005).

A production unit can be deemed eco-efficient when no improvement can be achieved in relation to any environmental objective without causing a decline in performance in relation to other environmental or economic objectives, 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 eco-efficient frontier in order to analyze differences in management and their environmental consequences.

Using Life Cycle Analysis (LCA) within a Data Envelopment Analysis (DEA) framework can enhance the eco-efficiency analysis of farming systems insofar as LCA provides a broader perspective of the environmental consequences of production. 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 […] 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, pp. 5-6).

In the last decade a burgeoning stream of literature has approached the analysis of the environmental impact of farming and agro-food industry by using a combined LCA-DEA methodology (see, for example, Avadí et al., 2014; Iribarren et al., 2010, 2011; Khoshnevisan et al., 2015; Lozano et al., 2009, 2010; Lorenzo-Toja et al., 2015; Mohammadi et al., 2013, 2015; Sanjuán et al., 2011; Vázquez-Rowe et al., 2010, 2012). The conventional LCA-DEA approach assesses the change in environmental impacts arising from the achievement of technical efficiency in the production process. However, technical efficiency does not necessarily mean eco-efficiency, and this has led us to introduce two main methodological changes. Firstly, we introduce a new approach in the LCA-DEA methodology to assess eco-efficiency directly in terms of the potential reduction in producers' environmental impacts, including savings due not only to technical efficiency, but also stemming from the use of inputs with less environmental impact. Secondly, we compare the eco-efficiency of production systems that operate under different technological constraints. In doing so we take advantage of the use of metafrontier (MF), which allows us to compare the performance of groups of producers using different technologies. Moreover, the use of directional distance functions (DDF) allows us to define a set of eco-efficiency indicators that respond to a variety of interests of researchers and policy-makers, and to highlight the strengths and weaknesses of each production unit and technology with respect to special features of its environmental performance.[1]

The empirical analysis reported in this paper aims to compare the eco-efficiency of Spanish conventional and organic citrus farming systems. We start by using LCA methodology to assess six different types of farm-level environmental impacts, including impact of cultivation and also that from the manufacturing of inputs. We then adopt a ratio indicator of eco-efficiency defined at farm level, where the value of production is related to a composite measure of environmental impacts, as defined by WBSCD (2000). Although no self-evident pattern of weights exists for this set of environmental impacts, the use of DEA allows an endogenous computation of weights.

After this introduction, we proceed in Section 2 to explain our methodological approach, while in Section 3 we show the general features of both citrus cultivation systems, describe variables and sample data, and perform LCA. Section 4 is devoted to the computation of the DEA model, as well as the presentation and discussion of our results, while Section 5 sets out the conclusions based on our findings.

2. Methodology

2.1. An introduction to LCA and DEA methodology

A basic tenet of our approach is the combination of LCA and DEA methodology to compare eco-efficiency for two technologically heterogeneous farming systems: organic and conventional citrus farming. LCA was first proposed in the late 1960s and early 1970s and over time has become one of the predominant quantitative tools used to measure environmental impacts, while also undergoing a substantial degree of international standardization in the process (Arvanitoyannis, 2008; Chang et al., 2014; Ji and Hong, 2016; Pryshlakivsky and Searcy, 2013). LCA is a methodology that basically converts inventory data of outputs and inputs of a system to a reduced number of environmental indicators, and traditionally consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.[2]

When the analysis of the environmental performance is focused on the performance of a productive sector as a whole, LCA has been frequently applied to average inventory data. Nevertheless, data variability concerning operational tasks may lead to high standard deviations in some environmental impacts, thus calling into question the reliability of the whole exercise. The greater the number of individual observations to which the LCA is applied, the more representative is 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 for a joint implementation of LCA and DEA, in order to handle information from a large number of individual

[1] Van Passel and Meul (2012) point to the importance of performing sustainability analysis at different levels (i.e., farm and sector level) in order to provide a better support in decision making.

[2] See Bidstrup (2015) for an analysis of the usefulness of life cycle thinking in impact assessment, Guinée et al. (2004) for a detailed operational description of LCA, 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 of eco-efficiency analysis.