Improving productivity and water use efficiency: a case study of farms in England

Article

Accepted Version

Gadanakis, Y., Bennett, R., Park, J. and Areal, F. J. (2015) Improving productivity and water use efficiency: a case study of farms in England. Agricultural Water Management, 160. pp. 22-32. ISSN 0378-3774 doi: https://doi.org/10.1016/j.agwat.2015.06.020 Available at http://centaur.reading.ac.uk/40537/

To link to this article DOI: http://dx.doi.org/10.1016/j.agwat.2015.06.020

Publisher: Elsevier

Improving productivity and water use efficiency: a case study of farms in East Anglia

Yiorgos Gadanakis*[a], Richard Bennett[a], Julian Park[a], Francisco Jose Areal[a]

[a] School of Agriculture, Policy and Development, University of Reading, Whiteknights, PO Box 237, Reading, RG6 6AR, UK

* Corresponding Author. Tel. +44 7799041241 - *e-mail addresses*: g.gadanakis@reading.ac.uk, grgadanakis@gmail.com (Y. Gadanakis)

Abstract

The idea of Sustainable Intensification comes as a response to the challenge of avoiding resources such as land, water and energy being overexploited while increasing food production for an increasing demand from a growing global population. Sustainable Intensification means that farmers need to simultaneously increase yields and sustainably use limited natural resources, such as water. Within the agricultural sector water has a number of uses including irrigation, spraying, drinking for livestock and washing (vegetables, livestock buildings). In order to achieve Sustainable Intensification measures are needed that enable policy makers and managers to inform them about the relative performance of farms as well as of possible ways to improve such performance. We provide a benchmarking tool to assess water use (relative) efficiency at a farm level, suggest pathways to improve farm level productivity by identifying best practices for reducing excessive use of water for irrigation. Data Envelopment Analysis techniques including analysis of returns to scale were used to evaluate any excess in agricultural water use of 66 Horticulture Farms based on different River Basin Catchments across England. We found that farms in the sample can reduce on average water requirements by 35% to achieve the same output (Gross Margin) when compared to their peers on the frontier. In addition, 47% of the farms operate under increasing returns to scale, indicating that farms will need to develop economies of scale to achieve input cost savings. Regarding the adoption of specific water use efficiency management practices, we found that the use of a decision support tool, recycling water and the installation of trickle/drip/spray lines irrigation system has a positive impact on water use efficiency at a farm level whereas the use of other irrigation systems such as the overhead irrigation system was found to have a negative effect on water use efficiency.

Keywords: *Data Envelopment Analysis, Water Use Efficiency, Technical Efficiency, Scale Efficiency, Benchmarking, East Anglia*

1. Introduction

Water is essential to agriculture production with uses comprising irrigation, spraying, drinking for livestock and washing (vegetables, livestock buildings). In the UK water for agriculture is obtained either directly from rivers and boreholes, or from the supply of mains waters as well as a combination of both (Defra, 2011). The effect of extreme weather phenomena associated with climate change on water availability has been studied (Chen et al., 2013; Daccache et al., 2011; Defra, 2009; Environment Agency, 2008; Jenkins et al., 2009). Most of these studies conclude that the availability of water for agriculture is under threat. The impacts for England in particular will be spatially and temporally variable (Defra, 2009). Therefore, future projections for reduced rainfall during spring and summer time and the increase in the average temperature will lead to more frequent and extensive drought[1] periods (Charlton et al., 2010). The recent dry periods of 2011 and 2012 caused increased pressures in UK water resources. In various catchments across the country, there was little or no water available for abstraction (FAS, 2013). Focusing on water use for irrigated root and vegetable crops, the continued production in the south and east of England will be dependent on the provision of adequate sources of water for irrigation. In addition, harvesting in wetter autumns could also be problematic (Charlton et al., 2010).

The main region within England for which water is crucial for agriculture production is the Anglian region where the main use of water is for irrigation, both for the production of cash crops as well as for horticulture. The average abstraction of water (excluding tidal) in the Anglian region for spray irrigation between 2000 and 2012 was 50.5 million m^3 accounting for the 59% of the average total water used in agriculture for England. In terms of number of abstraction licences in force for spray irrigation in 2012,

---

[1] "Drought is a nature produced but temporary imbalance of water availability, consisting of a persistent lower than average precipitation, of uncertain frequency, duration and severity, the occurrence of which is difficult to predict, resulting in diminished water resources availability and carrying capacity of the eco-systems". (Pereira et al., 2002)

the Anglian region accounts for the 38% of total licences in England[2]. Irrigation in the East Anglian River Basin Catchment (EARBC) and in the South East of England is mainly concentrated on cash-crop production (potatoes and sugar beet) as well as horticulture and therefore it is considered as a major production input to secure yield and income for the farmers, especially during dry periods. Irrigated production delivers substantial economic benefits not only at the farm gate but also beyond that point since it supports a number of related businesses that provide equipment and farm supplies and are also responsible for the promotion and distribution of production. It can therefore be considered as an important factor for the development of the rural economy in East Anglia (Knox et al., 2009) and other regions of England with horticulture production like the South East, Thames, Humber, South West, etc. river basin catchment areas. The EARBC and England in general may face high pressures in future due to both a) an increase in water abstraction rates for agriculture due to increased water demand and increased number of abstraction licences and b) a decrease in water availability associated with changing weather conditions. The main climate threats are temperature increase and reduced precipitation (Defra, 2009; Environment Agency, 2008, 2011) with direct impacts on the hydrology structure of the area.

The Environment Agency (EA) is the water regulatory authority for England and is also responsible for the authorisation of abstraction licences (Environment Agency, 2013). Its primary responsibility is to balance the water needs of all abstractors (all industries involved in water abstraction including agriculture) with that of the natural environment. The EA considers water use efficiency as a need to save and manage water efficiently whilst at the same time promoting environmental sustainability.

Irrigated agriculture in England has therefore to achieve two goals in order to secure the future growth and the economic sustainability of the sector. The first objective is to maintain and improve productivity in order to meet increasing future food demand (FAO, 2011) but at the same time to preserve the associated natural environment. Intensive agricultural practices combined with the probability of more

---

[2] Data comes from the "Water quality and abstraction statistics" published in the DEFRA website. The source of data is the Environment Agency. Available online at: https://www.gov.uk/government/statistical-data-sets/env15-water-abstraction-tables : Accessed on 26.12.2013

frequent dry periods in the area may increase the competition for water resources in an already over-abstracted and over-licensed catchment (Knox et al., 2009). The Sustainable Intensification (SI) of agricultural production is promoted as a mechanism that can balance the two objectives and at the same time mitigate any conflicts between these two objectives. More specifically, the SI of agriculture requires farmers to simultaneously increase their yields in order to meet the future demand for food, but also to reduce environmental pressures generated by the production process (Garnett and Godfray, 2012).

In this sense, agricultural productivity and water use efficiency should be considered together when evaluating the sustainability of farming systems. However, the social aim of sustainable farming systems (i.e. increase productivity, being water use efficient) does not necessarily match with farmers business aims (i.e. increase profitability). In order to close this gap between social and business objectives, farmers, need to demonstrate efficient water use for renewing an irrigation abstraction licence (Knox et al., 2012). For instance, a farmer may seek to maximise production and profit per unit of water (financial sustainability) while the goal of an environmentally sustainable system could be to minimise the use of water per value or volume of production (Knox et al., 2012). These contrasting approaches to efficiency and also between increasing agricultural productivity and environmental preservation require a management approach that simultaneously takes into consideration sustainability, productivity, and profitability (Vico and Porporato, 2011).

For most farmers in England involved in high value crop production water use for irrigation is driven by the need to produce a high quality product and hence obtain contracts and high prices from their customers, particularly supermarkets (Knox et al., 2012). Therefore, economic incentives can play a critical role in irrigation decisions (Oster and Wichelns, 2003). Knox et al. (2012) suggests that an economically rational farmer, when there are unlimited water resources, would aim to use water until the marginal benefit no longer exceeded the marginal cost. If the farmer fears that the water resources may be inadequate, irrigation is restricted to the most (financially) responsive crops. Water use efficiency is therefore considered as an economically driven parameter strongly related to the production and marginal profit of a farm. The Farm Business Survey in England 2009/2010 also recorded financial or customer reasons as the primary reasons (55%) for farmers carrying out management practices for efficient water use in irrigation (Defra, 2011).

In addition, Knox et al. (2012) suggest that excess irrigation is avoided when the farmer is aware of the risk of increased crop disease, has difficult land access and/or has concerns about the risk of fertiliser leaching. Most farmers therefore sensibly aim for best (or reasonable) use of a potentially limited water supply, aiming not to over or under irrigate (especially in the case of dry summers), whilst minimising any non-beneficial losses (e.g. run-off, leaching). This is often described as “applying the right amount of water at the right time in the right place”.

Water demanded for irrigation at a farm level depends on farmers’ decisions on when and which crop to produce, the volume and the frequency of irrigation and also the selection of irrigation method and technology (Marques et al., 2005). It is therefore a decision related to the production technology and the management ability of the farmer. Vico and Porporato (2011), note that there are a number of uncertainties in relation to both the economic and productivity goals of a farmer that increase the complexity of the choice of a sustainable and efficient water management strategy. These uncertainties are related to pests and diseases, temperature extremes, rainfall variability and timing in relation to crop growth stages, crop physiological properties and response to water availability. Further, they are confounded by differences in soil properties that determine water runoff and percolation (English et al., 2002). Among the above, rainfall variability (especially increased frequency of drought periods during the growing season) can significantly impact productivity and profitability (Vico and Porporato, 2011).

1.1. Measuring water use efficiency at a farm level

The vast majority of published research papers and reports on measuring water use efficiency focus on engineering and agronomic techniques. Under this framework, water use efficiency can be defined as the yield of harvested crop product achieved from the water available to the crop through rainfall, irrigation and the contribution of soil storage (Singh et al., 2010).

However, these approaches do not consider water as an economic good and therefore they do not allow the evaluation of the economic level of water use efficiency (Wang, 2010). The economic approach to defining and measuring water use efficiency is based on the concept of input specific technical efficiency

(Kaneko et al., 2004). Thus, water use at a farm level is used in combination with other inputs (land, labour, fertilisers, etc.) to estimate a production frontier which represents an optimal allowance of the inputs used. This methodology aims to assess farmers' managerial capability to implement technological processes (Karagiannis et al., 2003). In addition to management decisions, special regional characteristics (i.e. soil type and its available water capacity) can play a crucial role in influencing water application at farm level and therefore efficiency (Knox et al., 2012; Lilienfeld and Asmild, 2007).

In the literature there are broadly two approaches used to obtain efficiency estimates at a farm level; parametric techniques (i.e. Stochastic Frontier Analysis (SFA)) and non-parametric techniques (i.e. Data Envelopment Analysis (DEA)). Parametric techniques are used for the specification and estimation of a parametric production function which is representative of the best available technology (Chavas et al., 2005). The advantage of this technique is that it provides the researcher with a robust framework for performing hypothesis testing, and the construction of confidence intervals. However, its drawbacks lie in the *a priori* assumptions in relation to the functional form of the frontier technology and the distribution of the technical inefficiency term, in addition to the results being sensitive to the parametric form chosen (Wadud and White, 2000).

Due to the flexibility of DEA, in avoiding a parametric specification of technology and assumptions about the distribution efficiency but at the same time allowing for curvature conditions to be imposed, it is the preferred method for the analysis of technical and specific input (water use) efficiency in the EARBC over SFA. DEA is used to evaluate the performance efficiency of various Decision Making Units (DMU's) which convert multiple inputs into multiple outputs. It is a technique that provides a straightforward approach to measure the gap between each farmer's behaviour from best productive practices, which can be estimated from actual observations of the inputs and outputs of efficient firms (Lansink et al., 2002; Wang, 2010). The production frontier is constructed as a piecewise linear envelopment of the observed data points. This means that the best performing farms are identified as those using the least amounts of inputs to produce their individual levels of output. Linear, or convex, combinations of those best performers constitute the production frontier. The efficiency of the farms is then measured relative to this estimated frontier of best performers (Lilienfeld and Asmild, 2007).

Various research projects have used DEA for measuring water use efficiency at a farm level in areas where water use for irrigation is a critical issue in securing economic, social and environmental sustainability like in Mauritania, Tunisia, South Africa and other parts of the world with relative dry climate (Borgia et al., 2013; Chebil et al., 2012; Chemak, 2012; Frija et al., 2009; Lilienfeld and Asmild, 2007; Mahdi et al., 2008; Speelman et al., 2008; Veettil et al., 2011; Wang, 2010). The majority has used a sub-vector DEA model to estimate excess water use as proposed by Färe et al. (1994).

1.2. Objectives

There are two main objectives 1) to assess the technical efficiency of irrigating horticulture farms in England and 2) to provide an estimate of water use efficiency at farm level. For these we use a benchmarking technique with a sample of farms derived from the Farm Business Survey of 2009/2010. The identification of excessive water use at farm level can then be used to provide recommendations for improvements of management practices and policy interventions. In this research paper we consider water as an economic good and therefore an economic approach rather than an engineering approach is used to define and measure water use efficiency based on the concept of input specific technical efficiency. Excess water use has an economic impact (increased production costs) at a farm level but also can be a source of environmental degradation. In particular it not only reduces available water resources but also involves short and long term damage caused by surface runoff as a result of over application and deep percolation losses of water below the root zone which cannot be utilised by crops (Pimentel et al., 2004). Further, farmers that over abstract and overuse surface or ground water from an aquifer that is not adequately recharging due to drought imposes an opportunity cost on future generations (Oster and Wichelns, 2003) and threatens the sustainability of the ecosystem.

For the purposes of the analysis, water use efficiency is defined as the ratio of the minimum feasible water use (based on the non-radial notion of input specific technical efficiency (Fang et al., 2013)) to the observed water use at a farm level for irrigation, subject to the available production technology, the observed level of outputs and the use of other inputs (Matthews, 2013). It is therefore an input oriented measure of technical efficiency which allows for a radial reduction of water use at farm level (Wang, 2010). This approach allows for a specific input reduction (water) without altering the production output and the quantities of other inputs used. It is emphasised that in this sense, water use efficiency has an economic rather than an engineering meaning (Kaneko et al., 2004; Wang, 2010).

The development and implementation of integrated water management strategies and policies becomes a crucial decision to secure the sustainability of agricultural sector in specific parts of England (East Anglia, South East). This suggests a need to develop guidance on what should be measured and how data might be interpreted to demonstrate efficient use of water in agriculture (Knox et al. 2012). Considering this we conclude on specific recommendations for the data requirements necessary to measure water use efficiency at a farm level, based on the sub-vector efficiency approach. These are discussed in the context of the sustainable intensification of agriculture and climatic change.

1.3. Determinants of efficiency

Water use efficiency in agriculture can be influenced by various factors as they have been identified in the literature. Wang (2010) suggests that age, income, education level, farm size and the different irrigation systems are factors influencing water use efficiency. Moreover, Wang (2010) identified that exclusive water property rights as well as the competitive price mechanism had a strong influence in efficiency. The same structure parameters as above were regressed at a second stage by Mahdi et al. (2008), Lilienfeld and Asmild (2007) and Speelman et al. (2008). The latter, in addition, took into consideration as an influencing parameter the choice of crop, the landownership and the total cultivated area. The same approach was adapted by Wambui (2011) in the assessment of water use efficiency and its influencing parameters in the Naivasha lake basin. Structural and managerial characteristics were also proven to influence the technical performance of farms by Van Passel et al. (2007) who concluded that the same factors as mentioned above as well as the prospect of succession and dependency on subsidies are influencing efficiency.

2. Overview of the study area and data requirements

Data for the empirical application of the model have been obtained from the Farm Business Survey[3] (FBS) which is a comprehensive and detailed database that provides information on the physical and economic performance of farm businesses in England. The FBS uses a sample of farms that is representative of the national population of farms in terms of farm type, farm size and regional location. The FBS survey is carried out by the Rural Business Research and is the largest and most extensive business survey of farms in England. It is commissioned by the Department for Environment, Food and Rural Affair (DEFRA) and is also supported by the farming unions. There were in total 8,996 horticultural businesses in England. However, approximately half of these are regarded as being too small for inclusion in the FBS, as they fall below the minimum threshold. The sample size for 2009 cropping year was 212 businesses. Out of those farms, 151 participated in the water use survey of the FBS with an average of 95 ha main crop area and an average of 26 ha irrigated area. Hence, farms with a percentage of irrigated area over main crop area less than 90% were excluded from the sample. This criterion was set in order to ensure that the sample contained only horticulture farms that rely their production on irrigation. A sample of 74 Horticulture Farms was selected from the FBS 2009/2010 database. The majority of the farms are based in EARBC (25 farms) followed by farms based in the catchment area of South East (13 farms), Thames (9 farms), Humber (8 farms), South West (7 farms), Severn (7 farms), North West (3 farms) and Northumbria (2 farms). The average water use for irrigation for the sample is 2,710 m^3/ha.

In particular the 2009/2010 cropping year could be characterised as a period with a series of events strongly influencing both the area harvested and the growing conditions of crops. The 2009 spring was characterised by generally cool, dry conditions which facilitated agricultural operations and reduced crop disease pressure. However the 2009 harvest period was wet which also increased the concern of fungal

---

[3] For further information about the Farm Business Survey, including data collection, methodology and Farm Business Survey results, please visit the Rural Business Research website: http://www.fbspartnership.co.uk/index.php?id=1528

diseases in sugar beet and potatoes. Sugar beet harvest was disrupted by the exceptionally cold conditions in January 2010 causing also problems for the transport of the product to the market destinations. In regards to irrigation, substantially fewer farmers irrigated crops than held abstraction licences for spray irrigation, due in part to the dry conditions of 2009. In addition, since DEA methods are quite sensitive to the presence of outliers in the data when measuring efficiency (Sexton et al., 1986), eight farms were omitted from the initial sample, being identified as outliers based on the method described in (Wilson, 1993, 2010). These outlier farms would have had a strong influence on the construction of the benchmarking frontier and therefore could influence the results and the interpretation of the efficiency scores. The final number of farms in the research sample was 66. The graphical method of Wilson (1993) is presented in detail on the online appendix of this paper. In total, the sample includes 22 large, 24 medium and 20 small farms as well as 1 very small farm satisfying the need to account for all different farm sizes[4].

The horticulture farming systems[5] were selected over other agricultural systems mainly because of three reasons 1) their contribution to UK agricultural output (£2,504 million in 2009 and £3,007 million in 2013), 2) the demand of supplemented irrigation to secure yield (under drought conditions) and 3) because it is one of the most representative agricultural systems in East Anglia and South East (areas with high risk of drought and high demand for abstraction licences).

---

[4] In order to classify farms in the FBS into different sizes the Standard Labour Requirements (SLR) for different enterprises are calculated which are then used to find the total amount of standard labour used on the farm. Once the total annual SLR has been calculated the number of hours can be converted to an equivalent number of full time workers (on the basis that a full-time worker works a 39 hour week and so 1900 hours a year). This leads to the classification of farms by number of full time equivalent (FTE) workers as follows:
Small farms: 1<FTE<2, Medium farms: 2<FTE<3, Large farms: 3<FTE<5

[5] Holdings on which fruit (including vineyards), hardy nursery stock, glasshouse flowers and vegetables, market garden scale vegetables, outdoor bulbs and flowers, and mushrooms account for more than two thirds of their total Standard Outputs (SOs) which are calculated per hectare of crops (FBS 2009-2010).

The production technology for the estimation of technical and sub-vector efficiency was defined by the total area farmed, total agricultural costs (including fertiliser, crop protection and seed costs), other agricultural costs covering all costs with direct connection with crop production,energy costs including fuel and electricity costs, total labour hours per year and water use for irrigation in cubic meters. The data are aggregated at a farm level i.e. irrigation applications on different fields of the same farm are aggregated into a single variable. The output used in the DEA model was the gross margin at a farm level. The sample was selected in order to ensure the assumption of homogeneity in the DEA method. Table 1 presents a description of the sample used to build the input and output DEA model.

3. Methodology: Data Envelopment Analysis

In an input orientated framework for DEA, the best performing farms are identified as those that manage to produce the highest individual levels of output with the least amounts of inputs. Linear, or convex, combinations of those best performers constitute the production frontier. Since DEA is a benchmarking technique, the efficiency of the remaining farms is then measured relative to this estimated frontier of the best performers in the sample. A more detailed discussion of the different DEA models and the development of the techniques is available in (Cooper et al., 2007).

DEA models can be either input or output orientated assuming different types of returns to scale. For the purposes of this analysis an input orientated model with Variable Returns to Scale (VRS) was selected where efficiency scores indicate the total potential reduction for each input level while maintaining individual levels of outputs unchanged. VRS (Banker et al., 1984) are considered as the most appropriate in the case of agriculture (Asmild and Hougaard, 2006; Lilienfeld and Asmild, 2007). The alternative would have been to choose Constant Returns to Scale (CRS) assuming that when doubling all inputs, outputs will also double which is not a reasonable assumption in the case of agriculture. For example, a limiting production input is area farmed which is difficult to increase especially in the short run.

Furthermore, since the purposes of this research is to assess the inefficiency of water use for GCFs in the EARBC, a non-discretionary or sub-vector variation of the model for DEA was used.

To formalise the above let us assume that we observe a set of n farms and each farm $i = \{1, .., n\}$ has a set of inputs and outputs representing multiple performance measures. Considering then that each farm i uses J $(j = 1, \cdots, J)$ inputs, x_j to produce s outputs y_r $(r = 1, \cdots, s)$.

The general form of an input oriented DEA linear programming with all inputs variable is as follows:

$$
\begin{aligned}
& min_{\theta,\lambda^i}\, \theta' & & \\
s.t. \quad & \theta x'_{ji} \geq \textstyle\sum_{i=1}^{n} \lambda^i x_{ji} & & (i) \\
& y'_{ri} \leq \textstyle\sum_{i=1}^{n} \lambda^i y_{ri} & & (ii) \\
& \lambda^i \geq 0 & & (iii) \\
& \textstyle\sum_{i-1}^{n} \lambda^i = 1 & & (iv)
\end{aligned}
\qquad (1)
$$

Where θ' is a scalar, representing the efficiency score for each of the n farms. The estimate will satisfy the restriction $\theta_{i'} \leq 1$ with the value $\theta_{i'} = 1$ indicating an efficient farm. This is because the ratio is formed relative to the Euclidean distance from the origin over the production possibility set.

Also, in the above formulation we consider that there is a set of discretionary or variable inputs DI, $DI \subset \{1, \cdots, J\}$ and a set of non-discretionary inputs NDI, $NDI = \{1, \cdots, F\} \setminus DI = \{h \in \{1, \cdots, J\} \,|\, h \notin DI\}$ that cannot be adjusted or are held fixed at least in the short run. The combination of the DI and NDI variables defines therefore the technology set P:

$$\boldsymbol{P = \left\{ \left(x_{DIji}, x_{NDIji}, y_{ri} \right) \middle| x_{DIji} \; and \; x_{NDIji} \; can \; produce \; y_{ri} \right\}} \qquad (2)$$

As suggested by Bogetoft and Otto (2010) in cases where DI and NDI variables exist, a traditional and popular variation of the Farrell (1957) procedure is used to solve the linear DEA programme with respect to the largest proportional reduction in the DI variables alone.

$$\theta\left(\left(x_{DIji}, x_{NDIji}, y_{ri} \right); P \right) = min_{\theta} \left\{ \theta \middle| \left(\theta x_{DIji}, x_{NDIji}, y_{ri} \right) \in P \right\} \qquad (3)$$

The linear DEA programme can therefore be modified as follows where only the DI variables are reduced. Thus the irrigation, water use specific DEA efficiency score for observation x', θ', is estimated by the following linear programming (LP) problem:

$$\begin{aligned} & min_{\theta,\lambda^i}\ \theta' \\ & s.t. \quad \theta {x'}_{DIji} \geq \sum_{i=1}^{n} \lambda^i x_{DIji} \qquad j \in DI \quad (i) \\ & \qquad {x'}_{NDIji} \geq \sum_{i=1}^{n} \lambda^i x_{NDIji} \qquad j \in NDI \quad (ii) \\ & \qquad {y'}_{ri} \leq \sum_{i=1}^{n} \lambda^i y_{ri} \qquad (iii) \\ & \qquad \lambda^i \geq 0 \qquad (iv) \\ & \qquad \sum_{i-1}^{n} \lambda^i = 1 \qquad (v) \end{aligned} \tag{4}$$

In order to enable the solution of the above model, the DEA linear programming can be rewritten in the following form where fixed or non-discretionary inputs are treated as negative outputs in a input based mode (Bogetoft and Otto, 2010):

$$\begin{aligned} & min_{\theta,\lambda^i}\ \theta' \\ & s.t. \quad \theta {x'}_{DIji} \geq \sum_{i=1}^{n} \lambda^i x_{DIji} \qquad j \in DI \quad (i) \\ & \qquad -{x'}_{NDIji} \geq \sum_{i=1}^{n} \lambda^i (-x_{NDIji}) \qquad j \in NDI \quad (ii) \\ & \qquad {y'}_{ri} \leq \sum_{i=1}^{n} \lambda^i y_{ri} \qquad (iii) \\ & \qquad \lambda^i \geq 0 \qquad (iv) \\ & \qquad \sum_{i-1}^{n} \lambda^i = 1 \qquad (v) \end{aligned} \tag{5}$$

Where, x_{DIji} is the j^{th}discretionary input for farm i , x_{NDIji} is the j^{th} non-discretionary input for farm i and y_{ri} is the r^{th} output for farm i, $i = (1, \cdots n)$, $j = (1, \cdots m)\ and\ r = (1, \cdots s)$. The optimal value θ represents the sub-vector efficiency score for each farm and its values lie between 0 and 1. This efficiency score indicates how much a farm is able to reduce the use of its discretionary inputs (water use) without decreasing the level of outputs with reference to the best performers or benchmarking farms in the sample. The first two constraints limit the proportional decrease in both discretionary (equation-**5**$_{(i)}$) and non-discretionary (equation-**5**$_{(ii)}$) inputs, when θ is minimised in relation to the input use achieved by the best observed technology. The third constraint ensures that the output generated by the i^{th} farm is less than that on the frontier. All three constraints ensure that the optimal solution belongs to the production possibility set. The final constraint expressed by the equation $\mathbf{5}_{(iv)}$, called also the convexity constraint, ensures the VRS assumption of the DEA sub-vector model. Therefore, the non-discretionary inputs can be treated in the DEA model as negative outputs (Bogetoft and Otto, 2010). The CRS and VRS models differ only in that the former, but not the latter includes the convexity condition described by equation $\mathbf{5}_{(iv)}$ and its constraints in $\mathbf{5}_{(v)}$ (Cooper et al., 2007).

Considering the above, a farm that receives a sub-vector efficiency score equal to 1 is therefore a best performer located on the production frontier and has no reduction potential for water use. Hence, and since DEA is a benchmarking method, the farms with a sub-vector efficiency score equal to 1 will define the optimal water use at farm level. The efficiency score of the remaining farms in the sample is then measured relative to the farms defining the efficiency frontier (optimal water use). Any other score less than $\theta = 1$ indicates a potential reduction in water use, i.e. excess water is used at a farm level, thus this farm is considered as water use inefficient. To illustrate this with a numerical example let us assume that the optimal θ for a farm is 0.75 which means that this farm is able to produce the same level of output by using 75% of its current level of water (or reducing water use by 25%) when compared to the best performing technology in the sample. The excess water use can be calculated as:

$$(1-\theta)x_{DIji} \tag{6}$$

where θ is the sub-vector efficiency score, 1 identifies the optimal input, output ratio and x_{DIji} is the amount of water use at a farm level.

To illustrate better the difference between the sub-vector and the conventional DEA model we assume a two input one output case presented in Figure 1. The problem takes the i^{th} farm A and then seeks to radially contract the input vector, x_i, as much as possible, while remaining within the feasible input set. The inner-boundary of this set is a piecewise linear isoquant determined by the frontier data points (the efficient farms in the sample are F1 and F2). The radial contraction of the input vector x_i produces a projected point on the frontier surface (A^0).

This projected point is a linear combination of the observed data points, with the constraints ensuring that the projected point cannot lie outside the feasible set. The overall technical efficiency measure of farm A relative to the frontier is given by the ratio $\theta = 0A^0/0A$. In the case of measuring the sub-vector efficiency for input X_1 (water use), then water use (X_1) is reduced while holding X_2 (all the remaining inputs – agricultural crop production costs, area farmed, energy costs, etc.) and output (Gross Margin) constant. In the graph A is projected to A′ and sub-vector efficiency is given by the ratio θ′ = 0′A′/0′A.

3.1. The impact of the size of economies of scale on the productivity of the farm

The DEA model under the VRS assumption decomposes technical efficiency into pure technical efficiency (PTE) and scale efficiency (SE) (Färe et al., 1994). Therefore, by estimating technical efficiency scores under assumptions of CRS (TE_{CRS}) - known as a measure of overall technical efficiency (OTE) - and VRS (TE_{VRS}) one can measure the SE which measures the impact of scale size on the productivity of the farm. SE efficiency is therefore defined as follows:

$$SE = \frac{TE_{CRS}}{TE_{VRS}} \tag{7}$$

SE can take values between 0 and 1. When $SE = 1$ a farm is operating at optimal scale size and otherwise if $S < 1$. The information revealed by SE is used to indicate potential benefits from adjusting farm size. Furthermore, expression (**7**) can be used to decompose TE_{CRS} into two mutually exclusive and non-additive components, the pure technical efficiency (PTE) (estimated by the VRS specification) and SE.

$$TE_{CRS} = TE_{VRS} * SE \tag{8}$$

This allows insight into the source of inefficiencies. The TE_{VRS} of water use specifies the possible efficiency improvement that can be achieved without altering the scale of operations. Hence it is considered as a measure of the required reduction in water use to improve efficiency and management of water resources in the short run. On the other hand, the TE_{CRS} and SE measures require the farm to increase or decrease its scale of operation and therefore should be viewed as long run measures that aim to reduce water use for the long run improvement in efficiency.

One shortcoming of the measurement of SE is that when $SE < 1$ it is difficult to indicate whether the farm operates in an area of Increasing Returns to Scale (IRS), Decreasing Returns to Scale (DRS) or Constant Returns to Scale (CRS). For that reason a detailed analysis and discussion of the nature of Returns to Scale (RTS) is required. The nature of RTS is determined by the relationship of the proportion of inputs used to produce the output for a farm. Whether IRS, DRS or CRS prevail depends on the relationship between the proportional change of inputs and outputs (Varian H., 2010). This shortcoming can be bypassed if an additional DEA problem with non-increasing returns to scale (NIRS) is imposed. This can easily be achieved by substituting the $\sum_{i-1}^{n}\lambda^{i} = 1$ restriction in equation (**5**) with $\sum_{i-1}^{n}\lambda^{i} \leq 1$ and then calculating the relevant technical efficiency (TE_{NIRS}). According to Färe et al. (1985), these three estimated frontiers under CRS, VRS, and NIRS can be used to identify the returns to scale characteristics of the technology at any given point. Specifically, a) if $TE_{CRS} = TE_{NIRS} < TE_{VRS}$, the input-oriented projection of the VRS frontier is under increasing returns to scale b) if $TE_{VRS} = TE_{NIRS} > TE_{CRS}$, diminishing returns hold and c) constant returns to scale hold if and only if $SE = 1 = TE_{CRS} = TE_{NIRS} = TE_{VRS}$.

3.2. Econometric estimation of drivers of water use efficiency

Beyond the analysis of water use efficiency levels for each farm, a truncated regression model at a second stage was used to assess the impact of various managerial characteristics on the level of efficiency.

The hypotheses to be tested via these variables are the following:

A set of management practices and irrigation methods will have a positive impact into reducing water use inefficiency (reducing distance function to the DEA efficiency frontier) and will improve the performance and productivity of horticulture farms. In particular:

a) The establishment and use of rainwater collection systems will both have a positive economic impact (reduce cost of water) and will also have a positive environmental impact since it will reduce the volume of ground or surface water abstracted

b) A positive impact is assumed for the use of in-field soil moisture measurements (including feeling soil, crop inspection), the use of water balance calculations and the use of a decision support tool since these management practices will allow for the application of precision irrigation at a farm level

c) Moreover, the positive impact of the following irrigation systems and application is assumed; i) use of an irrigation system characterised as trickle/drip/spray, ii) use of a drip irrigation system iii) use of an overhead irrigation system iv) combinations of those.

d) Finally, the last assumption to be tested is the impact of optimising the irrigations systems used by the farmers or not.

Following the above description of the variables, the following econometric model is estimated:

$$
\begin{aligned}
WUEff_{it} = {} & \beta_0 + \beta_1 * RcollSyst_{it} + \beta_2 * InFieldM_{it} + \beta_3 * WatBalCal_{it} + \beta_4 * DecSuppT_{it} + \beta_5 * Recycl_{it} + \beta_6 \\
& * OptIrrigSyst_{it} + \beta_7 * OtherSyst + \beta_8 * Drip_{it} + \beta_9 * Overh_{it} \\
& + \beta_{10} * DripOverh_{it} + \beta_{11} * TrickOverh_{it} + \beta_{12} * DripTrick_{it} + \beta_{13} * DripTrickOver_{it} + \varepsilon_{it}
\end{aligned}
$$

Where, WUEff is the biased corrected water use efficiency (0< WUEff<1), RcollSyst, InFieldM, WatBalCal, DecSuppT, Recycl and OptIrrigSystem are dummy variables of the management practices for efficient water use at a farm level (1 = the management practice is applied, 0 = Otherwise i.e. no management practice is applied). The OtherSyst, Drip, Overh, DripOverh, TrickOverh, DripTrick and DripTrickOver are also dummy variables of the irrigation systems used at a farm level (1 = the irrigation system is used, 0 = Trickle Spray irrigation systems only). The descriptive statistics of the explanatory variables are presented in Table 2. In particular, OtherSyst variable refers to farms using (boom, rain gun and centre pivots or linear moves irrigation systems), Drip variable includes farms using only drip irrigation systems and Overh variable only overhead irrigation systems. Moreover, 4 dummy variables are used to express the use of combinations of irrigation systems: DripOver – Use of drip and overhead irrigation systems, TrickOverh – Use of trickle spray and overhead irrigation systems, DripTrick – Drip and Trickle irrigation systems and finally the DripTrickOver variable represents farms in the sample using a combination of the three aforementioned irrigation systems. The reference group used in the truncated regression is farms using Trickle Spray irrigation systems only.

Studies measuring productivity and efficiency using DEA to investigate the impact of environmental factors at a second stage analysis have suffered from two problems. 1) serial correlation among the DEA estimates and 2) correlation of the inputs and outputs used in the first stage with second-stage environmental variables (Simar and Wilson, 2007). A solution to these problems consists of bootstrapping the results to obtain confidence intervals for the first stage productivity or efficiency scores (Simar and Wilson, 1998, 2007).

The significance of the Simar and Wilson (2007) double bootstrap procedure derives from the bias corrected efficiency estimation of θ' (estimated by expression (5)). These estimates are used as parameters in a truncated regression model. The selection of the model was based on the fact that the outcome variable is restricted to a truncated sample of a distribution. Since the dependent variable can take values between zero and one, we have a left truncation of the sample (0≤biased corrected water use efficiency). It must be noted that a censored model (e.g. Tobit) would not have been appropriate in this case since water use efficiency data have the characteristics of truncated data – limited in the sample of interest. Furthermore, according to Simar and Wilson (2007) and Banker and Natarajan (2008) Tobit estimation in the second stage yields biased and inconsistent estimators. The main reason for the selection of the truncated model by Simar and Wilson (2007) is that the true efficiency estimates are unobserved and are replaced with DEA estimates of efficiency. A detailed presentation of the double bootstrapped procedure and the Algorithm 2 used in this paper is available in Simar and Wilson (2007) and also on the online appendix of the paper.

4. Results

The estimated mean of technical efficiency under the two different assumptions of VRS (PTE) and CRS (OTE) for the sample of irrigating horticulture farms was 0.85 (STD=0.20) and 0.74 (STD=0.28) respectively. This implies that the irrigating farms in the sample could on average reduce their inputs by 15% without any size adjustments (PTE is considered) and by 26% when size adjustments are made (OTE is considered), maintaining in both cases the same level of output. Table 3 presents statistical information and the distribution of PTE and OTE for the sample. The mean SE is 0.86 (STD=0.22) with 40% of the farms operating at their optimal scale (SE=1).

The mean sub-vector efficiency is 0.51 (STD=0.44) under the assumption of CRS (OTE), indicating that the observed value of outputs (Gross Margin) could have been maintained by keeping the level of other inputs constant whilst reducing water requirements by 49%. In addition, when VRS (PTE) are assumed the mean sub-vector efficiency for the horticulture farms in the sample is 0.65 (STD=0.41) indicating a reduction in water requirements by 35%. Table 4 presents the relationship between technical efficiency estimated by the conventional model (all inputs are discretionary) and the sub-vector model (water use is a discretionary input and the remaining inputs are considered as non-discretionary). Savings in water use were estimated through expression (6) by taking into consideration also the difference in technical and sub-vector efficiency estimates. In the case of medium and small size farms, water savings are estimated to 533 m^3/ha in average, while for large size farms this can be more than 1000 m^3/ha.

When returns to scale are considered in the analysis, 40% of the farms in the sample operate under constant returns to scale indicating that these farms are not required to adjust their scale of operation in order to improve efficiency in the long run. However, 18% of the irrigating horticulture farms are operating under DRS which imply a reduction in scale of operation in order to achieve input use efficiency and 47% of the farms are operating under IRS. The latter indicates that these farms need to shift down their long-run average cost curve and increase their size of operation in order to save costs (develop long term economies of scale). Table 5 presents information in relation to the returns to scale and farm size in the sample. It is interesting to note that a significant proportion of medium and small farms operate under IRS which implies that these farms can potentially increase output; and this increase will be proportionally greater than a simultaneous and equal percentage change in the use of inputs, resulting in a decline in average costs.

4.1. The econometric estimation of water use efficiency determinants

The average bias corrected water use efficiency (robust DEA estimate of efficiency) for the 62 irrigating horticulture farms in the sample was 0.40 (STD=24), while the average ordinary water use efficiency was 0.65. We need to note that for the second stage of the analysis, four farms were excluded from the sample since no irrigation systems or practices could be identified for them (no information was available in the FBS dataset).

Table 6 presents a summary of the results of the double bootstrapped truncated regression model following the method of Simar and Wilson (2007). It needs to be emphasised that the dependent variable in the model is the vector of the reciprocal of DEA estimate (distance function), estimated for the input oriented, variable returns to scale water use efficiency model. Hence, it measures inefficiency. The objective will be to minimise the distance to the frontier and therefore, the sign of the parameters with a positive impact on water use efficiency must be also positive. From the initial results it can be stated that the model is a good fit with the data (Wald Chi-square=40.17, $P<0.001$).

In terms of water use efficiency management practices at a farm level, the assumption that recycling water could have a positive impact on water use efficiency is sustained from the results since it is positive and significant at 0.05% level $(\beta_5 = 0.26,\ p - value < 0.05)$. For farmers with installed recycling water systems the predicted sub-vector water use efficiency score will increase by 0.26. Significant and also positive impact in increasing water use efficiency at a farm level has also the use of a decision support tool for irrigation $(\beta_4 = 0.24,\ p - value < 0.05)$. The assumption that farmers improve their water use efficiency by using in-field soil moisture measurement, water balance calculations, rainwater collection systems and an optimised irrigation systems is not sustained by the results.

In terms of irrigation systems used, our results indicate that the trickle/drip/spray lines irrigation system has a positive impact towards improving water use efficiency. In particular, the use of other irrigation systems (boom, rain gun and centre pivots or linear moves) when compared to the use of only trickle spray irrigation systems reduce water use efficiency by 0.25 $(\beta_7 = -0.25,\ p - value < 0.01)$. Similar negative impact to water use efficiency is observed for drip and overhead irrigation systems with a 0.43 $(\beta_8 = -0.43,\ p - value < 0.05)$ and 0.22 $(\beta_9 = -0.22,\ p - value < 0.01)$ reduction in sub-vector efficiency when compared to the use of only trickle spray irrigation systems by the farmers.

Moreover, the combination of trickle and overhead irrigation systems with the use of only trickle spray irrigation systems will also have a statistically significant and negative impact by reducing water use efficiency by 0.41 $(\beta_{11} = -0.41,\ p - value < 0.05)$. Any other combination of management practices as it is observed in Table 6 will have not statistically significant impact to water use efficiency.

5. Discussion and implications

The increased frequency of extreme weather phenomena (drought and flood periods) in the future for the UK will result to a higher risk with regards to securing yield and farm income. This, in addition to increased food demand, has raised the need for agricultural production systems to adapt in a challenging and insecure environment. Agriculture in the EARBC and also in the South East of England is vulnerable to water shortages due to the increasing risk of drought and over abstraction of water resources. In addition, considering the substantial financial benefits for irrigation, especially for high value crops and vegetables, any distortions in the supply of water for irrigation will have a significant impact on farmers' income. Therefore the efficient use of water resources becomes a joined priority within the framework of SI of agriculture which requires a sustainable end efficient management of natural resources.

The average sub-vector efficiency score of 0.65 for irrigating horticulture farms suggests that improvements can be made towards the management of water resources in agriculture. The generally prevailing dry conditions of the 2009/2010 production year increased the demand for water resources and this can partly explain the excess of water use in the sample. Especially when areas such as the East Anglia and the South East of England are considered as two of the highest risk of drought areas in the country.

Regarding returns to scale, pathways for the improvement of productivity and maximisation of net benefits given the limited land and water resources are suggested. Specifically, 47% of the farms operate on the downward sloping part of the long run average cost curve. There is a potential therefore to increase production and hence profitability. This information, in addition to the results derived from the PTE analysis; indicate also a need for change in the management of inputs in the short run in order to improve control over the production process. On the other hand 18% of the farms are either producing above their profit maximising level of outputs or using excessive amounts of inputs per unit of output. The latter is confirmed by the level of inefficiency of water use based on the sub-vector model (Table 3).

Around 36% of the farms in the sample are abstracting water directly from bore holes, river streams, ponds, lakes and reservoirs. Irrigation water demand for the remaining 70% of the farms is supplied by water companies. The average cost of water supplied for irrigation by water companies is £2.59/ m^3 (STD=5.55, Trimmed Median =£1.13). According to the results presented in Table 4, the average potential savings in cost of water used for irrigation that can be achieved is 649 £/farm in a year. Hence, the adoption of efficient water recycling systems as these are identified by the results of the second stage regression analysis of this paper and the use of a decision for irrigation support tool can potentially reduce significantly input costs and also improve production efficiency. The installation and use of a recycling water systems can increase water use efficiency score by 0.26.

The use of a rainwater harvesting system to supply water for irrigation was not found as a management system with a statistically significant impact on water use efficiency. The reason for the low adoption of rainwater harvesting systems is that currently cannot compete financially with direct abstraction or mains supply but it can potentially be considered as an area for future development in UK irrigated farming systems (Weatherhead et al., 1997). Farms that adopt rainwater harvesting systems could potentially reduce mains water consumption, and hence input cost, and also to reduce their environmental impact. Further research is required to explore the full potential of the installation of rainwater harvesting systems in irrigation farming systems in England.

In order to renew their abstraction licences farmers are required to demonstrate efficient use of water resources to the regulator (Environment Agency, 2013). The results from the sub-vector model confirm that almost half of the farms (53%) in England are on the frontier and hence avoid any excess in water use when compared with peer farms in the sample. Knox et al. (2012) refers to the "Save water, save money[6]" booklet produced in 2007 and distributed to 2500 farmers across England to promote the "pathway to efficiency". The main components of the pathway include that farmers understand their system of production, make efforts to optimise the use of their irrigation systems, ensure appropriate soil and water management and demonstrate best practices that have proved over time to lead to more efficient irrigation (Knox et al., 2012).

The profile of the best performing irrigating farms in our sample resulting from the study of the farms on the frontier can be used as a good practice example to promote water use efficiency in England. The installation and use of a trickle/drip/spray lines irrigation system as it was shown by the results of the second stage analysis can increase water use efficiency when compared to other irrigation systems used by the sample. The spray type trickle irrigation systems have the advantage that are less likely to clog when compared to subsurface and drip systems, can improve crop yields and reduce water use and energy consumption at a farm level (James, 1988). These irrigation systems belong to the general

---

[6] The information booklet is available for download from the UK Irrigation Association website:

http://www.ukia.org/pdfs/Save%20water%20save%20money.pdf category of micro-irrigation systems that include various low rate emission devices such as drip irrigation, subsurface irrigation, bubbler irrigation and many other. However, on the other hand the use of drip irrigation systems by the farms on the sample had a negative impact on water use efficiency.

The use of efficient irrigation systems has the potential to reduce environmental risks due to leakages and excess of nutrients which could damage biodiversity and water quality. In addition, these systems could be also used for fertiliser application in the field. Moreover, spray type trickle irrigation can be used to maintain the water content of the root zone near the optimal level and hence, improve productivity (Mays, 2010).

In comparison to the trickle/drip/spray line irrigation systems, the use of an overhead sprinkle irrigation system has a statistically significant negative impact on water use efficiency. In particular it reduces the level of water use efficiency by 0.22. Although overhead sprinkle irrigation systems can improve the efficiency of crop development and water application due to the uniformity in water distribution, it is also a high and continuous energy demanding system which under poor weather conditions (strong wind and high temperature) increases the potential for water use excess and inefficiency.

The two management practices with a positive and statistically significant impact on improving water use efficiency are the use of a decision support tool and recycling water used. The use of a decision support tool for short and long term irrigation planning and monitoring has a positive impact into reducing water use inefficiency and hence pushing the farms towards the frontier. Such a tool could potentially provide farmers with options to support management decisions to improve economic and water efficiency as well as the environmental performance (reducing wastage) of the farming system (Khan et al., 2010).

Furthermore, in-field soil moisture measurement (including assessing the soil and crop inspection) and water balance calculations are management practices applied by the peer farms which enable them to schedule irrigation better and hence provide the optimal application of water at the right time and volume. However, these have no statistically significant impact on water use efficiency.

Furthermore, as it was shown from the regression analysis the set of water use efficiency irrigation management practices and systems with a positive and statistically significant impact on water use efficiency (recycling water, decision support tool and the use of trickle/drip/spray lines irrigation systems) can be an effective strategy to reduce runoff and significantly contribute to the reduction of diffuse pollution which is in line to the findings of the MOPS2 project (Deasy et al., 2010). Such practices will improve water quality and also enable UK agriculture to meet the requirements of the EU water framework directive.

6. Conclusions

Water for agriculture in the EARBC, in the South East of England and in other regions of the country may be becoming scarcer and more variable due to the increased abstraction rates and the increased occurrence of drought phenomena during the crop development period. Nationally there is a need to secure production in order to meet increasing food demand and thus supplementary irrigation of crops increases the pressure on water resources in water catchments across England. To ensure the sustainability of farming systems in the area, farmers need to both maximise economic productivity and efficiency while directing their strategies towards minimising excess of water for irrigation and other agricultural uses (washing, spraying).

A benchmarking technique such as DEA can provide a useful tool to identify excess water use when comparing farms with others in the same region and with the same characteristics and therefore help to improve water use efficiency at farm level. Moreover, peer farms (farms on the frontier) can provide useful information in respect of operational and management changes that can be made to improve irrigation system performance and water productivity. In addition, the analysis on returns to scale provides pathways for long term improvements and planning which could be used to strategically position a farm in relation to the long term average cost curve and hence improve economic efficiency and productivity.

From a policy perspective, the current water abstraction regulation in the UK is under reform. The main pillars of the reform are based on the need to face challenges in water availability due to changing weather conditions, the increased demand for water from growing population and the need to enable trading of water rights (Defra, 2013). Our results suggest that the new legislation should incentivise farmers to improve management practices for efficient water for irrigation and also improve water storage at farm level through rain harvesting and on farm reservoirs. Furthermore, it is essential that any reform accounts for the importance of supplementary irrigation for cash crops (potatoes, sugar beet) and the need to secure yield. Any restriction on water abstraction during the growth period due to water shortages or drought conditions would result to failure in meeting quality standards and consequently income loss to farmers. Therefore, it is important that the new regime considers the economic significance off irrigated agriculture not only for the farming systems but also for the local jobs and local economies.

Acknowledgments

The authors wish to thank the University of Reading for funding this research and also the Agriculture, Food and Investigation Team of the University of Reading for providing technical assistance and guidance over the use of FBS data. Special thanks go to two anonymous reviewers that with their constructive comments helped us to improve the final manuscript.

References

Asmild, M., Hougaard, J.L. (2006). Economic versus environmental improvement potentials of Danish pig farms. *Agricultural Economics, 35*(2), 171-181. doi: http://dx.doi.org/10.1111/j.1574-0862.2006.00150.x

Banker, R.D., Charnes, A., Cooper, W.W. (1984). Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. *Management Science, 30*(9), 1078-1092. doi: http://dx.doi.org/10.1287/mnsc.30.9.1078

Banker, R.D., Natarajan, R. (2008). Evaluating Contextual Variables Affecting Productivity Using Data Envelopment Analysis. *Operations Research, 56*(1), 48-58. doi: http://dx.doi.org/10.1287/opre.1070.0460

Bogetoft, P., Otto, L., 2010. Benchmarking with DEA, SFA, and R. Springer, New York.

Borgia, C., García-Bolaños, M., Li, T., Gómez-Macpherson, H., Comas, J., Connor, D., Mateos, L. (2013). Benchmarking for performance assessment of small and large irrigation schemes along the Senegal Valley in Mauritania. *Agricultural Water Management, 121*(0), 19-26. doi: http://dx.doi.org/10.1016/j.agwat.2013.01.002

Charlton, M., Bailey, A., Arnell, N., 2010. Water for Agriculture - Implications for Future Policy and Practice: Reviewing and modelling the impacts of climate change in future food production. Royal Agricultural Society of England.

Chavas, J.P., Petrie, R., Roth, M. (2005). Farm household production efficiency: Evidence from The Gambia. *American Journal of Agricultural Economics, 87*(1), 160-179. doi: http://dx.doi.org/10.1111/j.0002-9092.2005.00709.x

Chebil, A., Frija, A., Abdelkafi, B. (2012). Irrigation water use efficiency in collective irrigated schemes of Tunisia: determinants and potential irrigation cost reduction. *Agricultural Economics Review 13*(1), 39-48. doi: http://www.eng.auth.gr/mattas/13_1_3.pdf

Chemak, F. (2012). The Water Demand Management by Monitoring the Technology Performance and the Water Use Efficiency. *American Journal of Environmental Sciences, 8*(3), 241-247. doi: http://dx.doi.org/10.3844/ajessp.2012.241.247

Chen, Y., Du, J., Huo, J. (2013). Super-efficiency based on a modified directional distance function. *Omega, 41*(3), 621-625. doi: http://dx.doi.org/10.1016/j.omega.2012.06.006

Cooper, W., Seiford L. M, Tone K., 2007. Data Envelopment Analysis. A Comprehensive Text with Models, Applications, References and DEA-Solver Software Second Edition ed.

Daccache, A., Weatherhead, E.K., Stalham, M.A., Knox, J.W. (2011). Impacts of climate change on irrigated potato production in a humid climate. *Agricultural and Forest Meteorology, 151*(12), 1641-1653. doi: http://dx.doi.org/10.1016/j.agrformet.2011.06.018

Deasy, C., Quinton, J.N., Silgram, M., Stoate, C., Jackson, R., Stevens, C.J., Bailey, A.P. (2010). Mitigation Options for Phosphorus and Sediment (MOPS): Reducing Pollution in Runoff from Arable Fields. *The Environmentalist*(180), 12-17. doi: http://oro.open.ac.uk/id/eprint/25494

Defra, 2009. Adapting to Climate Change: UK Climate Projections, in: Department for Environment Food & Rural Affairs (Ed.). Defra, London.

Defra, 2011. Water Usage in Agriculture and Horticulture. Results from the Farm Business Survey 2009/10 and the Irrigation Survey 2010, in: Department for Environment Food & Rural Affairs (Ed.). National Statistics.

Defra, 2013. Making the most of every drop: Consultation on reforming the water abstraction system, in: Affairs, D.f.E.F.R. (Ed.). Defra, London.

English, M.J., Solomon, K.H., Hoffman, G.J. (2002). A paradigm shift in irrigation management. *Journal of Irrigation and Drainage Engineering-Asce, 128*(5), 267-277. doi: http://dx.doi.org/10.1061/(Asce)0733-9437(2002)128:5(267)

Environment Agency. (2008). Water resources in England and Wales - current state and future pressures. *Bristol: Environment Agency*.

Environment Agency. (2011). The case of change-current and future water availability. *Bristol: Environment Agency*, 41.

Environment Agency. (2013). Managing water abstraction. *Bristol: Environment Agency*, 29.

Fang, H.-H., Lee, H.-S., Hwang, S.-N., Chung, C.-C. (2013). A slacks-based measure of super-efficiency in data envelopment analysis: An alternative approach. *Omega, 41*(4), 731-734. doi: http://dx.doi.org/10.1016/j.omega.2012.10.004

FAO, 2011. Save and Grow: A policymaker's guide to the sustainable intensification of smallholder crop production. Food and Agriculture Organization of the United Nations, Rome.

Färe, R., Grosskopf, S., Lovell, C.A.K., 1985. The Measurement of Efficiency of Production. Springer.

Färe, R., Grosskopf, S., Lovell, C.A.K., 1994. Production frontiers. Camridge University Press, Cambridge.

Farrell, M.J. (1957). The Measurement of Productive Efficiency. *Journal of the Royal Statistical Society. Series A (General), 120*, 253-290. doi: http://dx.doi.org/10.2307/2343100

FAS, 2013. Cutting farm costs by improving water use efficiency, in: Farming Advice Service (Ed.). Department for Environment, Food and Rural Affairs.

Frija, A., Chebil, A., Speelman, S., Buysse, J., Van Huylenbroeck, G. (2009). Water use and technical efficiencies in horticultural greenhouses in Tunisia. *Agricultural Water Management, 96*(11), 1509-1516. doi: http://dx.doi.org/10.1016/j.agwat.2009.05.006

Garnett, T., Godfray, C., 2012. Sustainable intensification in agriculture. Navigating a course through competing food system priorities. Food Climate Research Network and the Oxford Martin Programme on the Future of Food, University of Oxford, UK.

James, L.G., 1988. Principles of farm irrigation systems design. John Wiley and Sons Limited.

Jenkins, G., Murphy, J., Sexton, D., Lowe, J. (2009). UK Climate Projections: Briefing Report. *Fifth report of the UKCP09 scientific reports, 5*, Available online: http://ukclimateprojections.defra.gov.uk.

Kaneko, S., Tanaka, K., Toyota, T., Mangi, S. (2004). Water efficiency of agricultural production in China: regional comparison from 1999 to 2002. *International Journal of Agricultural Resources, Governance and Ecology, 3*, 231-251. doi: http://dx.doi.org/10.1504/IJARGE.2004.006038

Karagiannis, G., Tzouvelekas, V., Xepapadeas, A. (2003). Measuring irrigation water efficiency with a stochastic production frontier - An application to Greek out-of-season vegetable cultivation. *Environmental & Resource Economics, 26*(1), 57-72. doi: http://dx.doi.org/10.1023/A:1025625402762

Khan, S., Mushtaq, S., Chen, C. (2010). A decision support tool for irrigation infrastructure investments. *Irrigation and Drainage, 59*(4), 404-418. doi: http://dx.doi.org/10.1002/ird.501

Knox, J., Weatherhead, K., Díaz, J.R., Kay, M. (2009). Developing a strategy to improve irrigation efficiency in a temperate climate: A case study in England. *Outlook on Agriculture, 38*(4), 303-309. doi: http://dx.doi.org/10.5367/000000009790422160

Knox, J.W., Kay, M.G., Weatherhead, E.K. (2012). Water regulation, crop production, and agricultural water management-Understanding farmer perspectives on irrigation efficiency. *Agricultural Water Management, 108*(0), 3-8. doi: http://dx.doi.org/10.1016/j.agwat.2011.06.007

Lansink, A.O., Pietola, K., Bäckman, S. (2002). Effciency and productivity of conventional and organic farms in Finland 1994–1997. *European Review of Agricultural Economics, 29*(1), 51-65. doi: http://dx.doi.org/10.1093/erae/29.1.51

Lilienfeld, A., Asmild, M. (2007). Estimation of excess water use in irrigated agriculture: A Data Envelopment Analysis approach. *Agricultural Water Management, 94*(1-3), 73-82. doi: http://dx.doi.org/10.1016/j.agwat.2007.08.005

Mahdi, N., Sghaier, M., Bachta, M.S. (2008). Technical efficiency of water use in the irrigated private schemes in Smar watershed, south-eastern Tunisia. *Options Mediterraneenes, Series A, 88*, 289-300.

Marques, G.F., Lund, J.R., Howitt, R.E. (2005). Modeling irrigated agricultural production and water use decisions under water supply uncertainty. *Water Resources Research, 41*(8), W08423. doi: http://dx.doi.org/10.1029/2005wr004048

Matthews, K. (2013). Risk management and managerial efficiency in Chinese banks: A network DEA framework. *Omega, 41*(2), 207-215. doi: http://dx.doi.org/10.1016/j.omega.2012.06.003

Mays, L.W., 2010. Water Resources Engineering. John Wiley & Sons.

Oster, J.D., Wichelns, D. (2003). Economic and agronomic strategies to achieve sustainable irrigation. *Irrigation Science, 22*(3-4), 107-120. doi: http://dx.doi.org/10.1007/s00271-003-0076-4

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E., Nandagopal, S. (2004). Water resources: Agricultural and environmental issues. *BioScience, 54*(10), 909-918. doi: http://dx.doi.org/10.1641/0006-3568(2004)054[0909:Wraaei]2.0.Co;2

Sexton, T.R., Silkman, R.H., Hogan, A.J. (1986). Data envelopment analysis: Critique and extensions. *New Directions for Program Evaluation, 1986*(32), 73-105. doi: http://dx.doi.org/10.1002/ev.1441

Shephard, R.W., 1970. Theory of Cost and Production Functions. Princenton University Press.

Simar, L., Wilson, P.W. (1998). Sensitivity analysis of efficiency scores: How to bootstrap in nonparametric frontier models. *Management Science, 44*(1), 49-61. doi: http://dx.doi.org/10.1287/Mnsc.44.1.49

Simar, L., Wilson, P.W. (2007). Estimation and inference in two-stage, semi-parametric models of production processes. *Journal of Econometrics, 136*(1), 31-64. doi: http://dx.doi.org/10.1016/j.jeconom.2005.07.009

Singh, R., Kundu, D.K., Bandyopadhyay, K.K. (2010). Enhancing Agricultural Productivity through Enhanced Water Use Efficiency. *Journal of Agricultural Physics, 10*, 1-15.

Speelman, S., D'Haese, M., Buysse, J., D'Haese, L. (2008). A measure for the efficiency of water use and its determinants, a case study of small-scale irrigation schemes in North-West Province, South Africa. *Agricultural Systems, 98*(1), 31-39. doi: http://dx.doi.org/10.1016/j.agsy.2008.03.006

Van Passel, S., Nevens, F., Mathijs, E., Van Huylenbroeck, G. (2007). Measuring farm sustainability and explaining differences in sustainable efficiency. *Ecological Economics, 62*(1), 149-161. doi: http://dx.doi.org/10.1016/j.ecolecon.2006.06.008

Varian H., 2010. Intermediate Microeconomics: A Modern Approach, Eighth Edition ed. W. W. Norton & Company.

Veettil, C.P., Ashok, A., Speelman, S., Buysse, J., Van Huylenbroeck, G. (2011). Sub-vector Efficiency analysis in Chance Constrained Stochastic DEA: An application to irrigation water use in the Krishna river basin, India. *Paper provided by European Association of Agricultural Economists in its series 122nd Seminar, February 17-18, 2011, Ancona, Italy with number 98978*(98978).

Vico, G., Porporato, A. (2011). From rainfed agriculture to stress-avoidance irrigation: II. Sustainability, crop yield, and profitability. *Advances in Water Resources, 34*(2), 272-281. doi: http://dx.doi.org/10.1016/j.advwatres.2010.11.011

Wadud, A., White, B. (2000). Farm household efficiency in Bangladesh: a comparison of stochastic frontier and DEA methods. *Applied Economics, 32*(13), 1665-1673. doi: http://dx.doi.org/10.1080/000368400421011

Wambui, N.G., 2011. An assesment on water efficiency in lake Naivasha Basin, in Kenya. Deapartment of Agricultural Economics University of Nairombi.

Wang, X.Y. (2010). Irrigation Water Use Efficiency of Farmers and Its Determinants: Evidence from a Survey in Northwestern China. *Agricultural Sciences in China, 9*(9), 1326-1337. doi: http://dx.doi.org/10.1016/S1671-2927(09)60223-6

Weatherhead, E., Knox, J.W., Morris, J., Hess, T.M., Bradley, R.I., Sanders, C.L. (1997). Irrigation demand and on-farm water conservation in England and Wales.

Wilson, P.W. (1993). Detecting Outliers in Deterministic Nonparametric Frontier Models with Multiple Outputs. *Journal of Business & Economic Statistics, 11*(3), 319-323. doi: http://dx.doi.org/10.2307/1391956

Wilson, P.W., 2010. Detecing outliers in deterministic nonparametric frontier models with multiple outputs: Correction, unpublished working paper. Department of Economics, Clemson University, Clemson, South Carolina 29634, available on-line at http://www.clemson.edu/economics/faculty/wilson/Papers/ap-corrected.pdf.

Table 1: Descriptive statistics of the inputs and the outputs used in the DEA linear programming model

Inputs and outputs for the DEA model	**Irrigating Horticulture Farms**	
	Mean	**St. Deviation**
Area farmed (ha)	7.172	12.17
Total agricultural costs (£/ha)	18,564	36,440
Water use (m^3/ha)	2,709	3,713
Energy cost (£/ha)	1,715	2,400
Total labour (hours/ha)	2,340	3,505
Other agricultural costs (£/ha)	10,117	18,629
Gross Margin (£/ha)	41,583	60,607

Table 2: Descriptive statistics of the variables used for the econometric estimation of the impact of management practices on water use efficiency

Variables used in the second stage truncation regression model	Irrigating Horticulture Farms	
	Mean/No of cases	St. Deviation
Bias-corrected water use efficiency	0.40	0.24
Rainwater collection systems	13	
In-field soil moisture measurement	24	
Water balance calculations	13	
Decision support tool	11	
Recycling	6	
Optimised irrigation systems	30	
Trickle/drip/spray lines irrigation system	33	
Other irrigation systems	14	
Drip irrigation systems	2	
Overhead irrigation systems	12	
Combine Drip and Overhead irrigation systems	2	
Combine Trickle Spray and Overhead irrigation systems	5	
Combine Drip and Trickle Spray irrigation systems	4	
Combine Drip, Trickle Spray and Overhead irrigation systems	2	

Table 3: Frequency distribution of technical and water use efficiency under the assumptions of CRS and VRS, and mean of SE.

Irrigating horticulture farms				
	Technical efficiency		**Water Use Efficiency**	
Efficiency level (%)	CRS	VRS	CRS	VRS
	Number of farms	Number of farms	Number of farms	Number of farms
0<Eff<30	6	1	29	20
30<Eff<50	8	4	6	7
50<Eff<70	12	15	3	1
70<Eff<100	14	11	2	3
Eff=100	26	35	26	35
Mean Efficiency	**0.74**	**0.85**	**0.51**	**0.65**
Mean Scale Efficiency	**0.86**		**0.67**	

Table 4: Estimated technical efficiency, sub-vector efficiency and water excess for the farms in the sample

FarmID	Water Use (m^3/ha	Technical Efficiency VRS	Water Use Efficiency VRS	Water Savings (m^3/ha)
1	172.61	0.45	0.15	52.15
5	472.24	0.70	0.17	250.05
6	5321.00	0.72	0.35	1973.03
7	1120.93	0.93	0.75	203.34
9	439.00	0.69	0.25	193.16
10	4012.41	0.79	0.25	2183.95
13	4351.47	0.64	0.08	2445.53
14	4735.00	0.58	0.32	1237.26
15	3492.86	0.94	0.65	1015.02
18	5250.00	0.79	0.31	2548.88
20	1929.17	0.81	0.21	1155.38
26	3148.15	0.74	0.35	1212.98
32	379.21	0.45	0.02	164.73
34	1520.60	0.69	0.07	942.01
36	2744.87	0.77	0.44	896.75
37	5509.08	0.70	0.12	3155.60
42	3333.33	0.69	0.22	1569.33
43	329.86	0.56	0.04	170.77
44	2992.86	0.89	0.82	196.33
50	899.00	0.70	0.11	526.18
52	3308.57	0.59	0.37	706.38
53	5384.62	0.53	0.13	2138.23
54	2585.54	0.67	0.01	1689.65
57	3971.63	0.56	0.13	1709.79
60	325.00	0.20	0.05	51.06
63	4227.27	0.97	0.94	135.27

Table 5: Returns to scale in relation to farm size

Group	Returns to Scale	Farm Size			%
		Large	Medium	Small	
Horticulture Farms	CRS	8	11	7	40
	DRS	8	1	0	14
	IRS	6	12	13	47

Table 6: Truncated regression. The dependent variable is the vector of the reciprocal of DEA estimate (distance function), estimated in the input-oriented sub-vector DEA model with variable returns of scale assumption.

	Observed Coef.	Std. Err.	t-value
(Intercept)	0.38 ***	0.06	6.44
Rainwater collection systems	0.11	0.09	1.12
In-field soil moisture measurement	0.03	0.07	0.50
Water balance calculations	-0.09	0.10	-0.89
Decision support tool	0.24 *	0.11	2.21
Recycling	0.26 *	0.13	2.01
Optimised irrigation system	0.03	0.09	0.34
Other irrigation systems	-0.25 **	0.10	-2.58
Drip irrigation systems	-0.43 *	0.18	-2.37
Overhead irrigation systems	-0.22 **	0.08	-2.59
Combine Drip and Overhead irrigation systems	-0.11	0.18	-0.62
Combine Trickle Spray and Overhead irrigation systems	-0.41 *	0.19	-2.21
Combine Drip and Trickle Spray irrigation systems	0.09	0.13	0.72
Combine Drip, Trickle Spray and Overhead irrigation systems	-0.19	0.18	-1.05
Sigma	-1.47 ***	0.10	-14.74

Signif. codes: ‘***’ 0.001, ‘**’ 0.01, ‘*’ 0.05, ‘.’ 0.1, ‘ ’ 1 – No of Bootstraps 2000
Log likelihood=-6.21
Wald $\chi^2(15) = 40.17$, Prob > χ^2 = 0.00

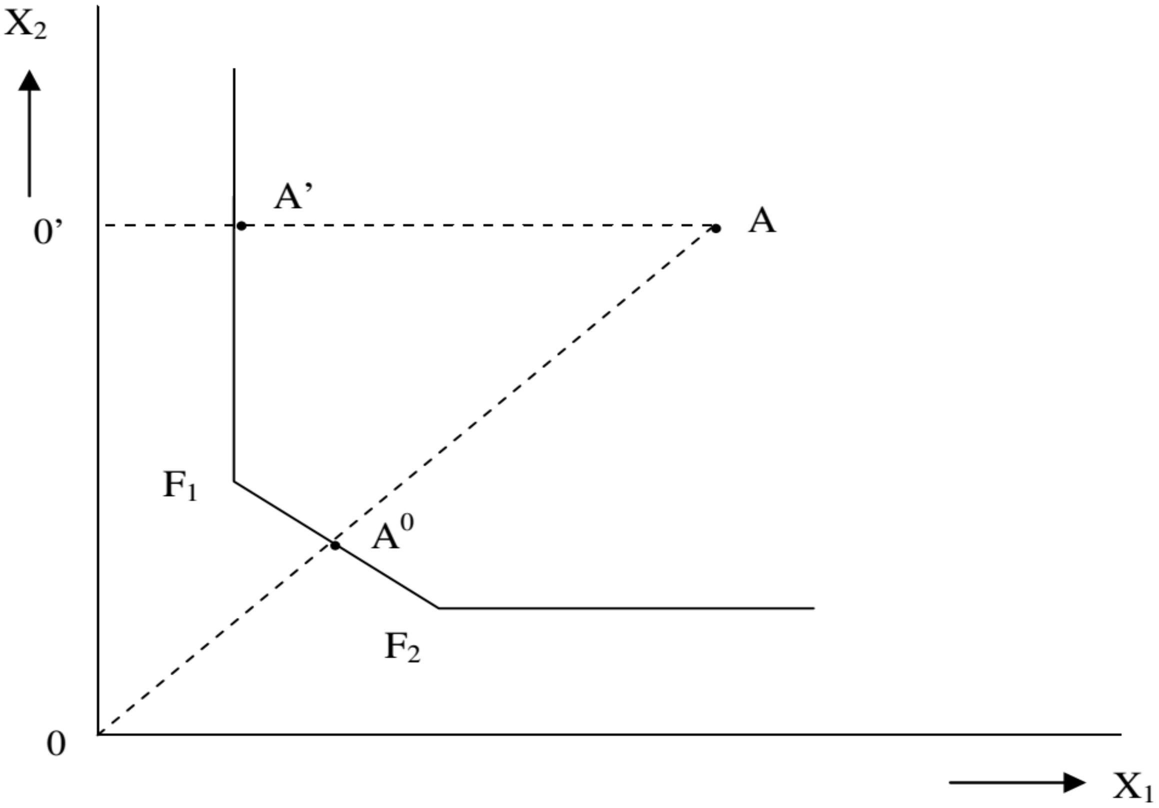

Figure 1: Graphical representation of the measurement of technical efficiency and sub-vector efficiency using DEA for an example with two inputs and one output (adapted from Lansink et al. (2002))