

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

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

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7 **Abstract**

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

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

30 **1. Introduction**

31 Water is essential to agriculture production with uses comprising irrigation, spraying, drinking for
32 livestock and washing (vegetables, livestock buildings). In the UK water for agriculture is obtained either
33 directly from rivers and boreholes, or from the supply of mains waters as well as a combination of both
34 (Defra, 2011). The effect of extreme weather phenomena associated with climate change on water
35 availability has been studied (Chen et al., 2013; Daccache et al., 2011; Defra, 2009; Environment
36 Agency, 2008; Jenkins et al., 2009). Most of these studies conclude that the availability of water for
37 agriculture is under threat. The impacts for England in particular will be spatially and temporally variable
38 (Defra, 2009). Therefore, future projections for reduced rainfall during spring and summer time and the
39 increase in the average temperature will lead to more frequent and extensive drought¹ periods (Charlton
40 et al., 2010). The recent dry periods of 2011 and 2012 caused increased pressures in UK water
41 resources. In various catchments across the country, there was little or no water available for abstraction
42 (FAS, 2013). Focusing on water use for irrigated root and vegetable crops, the continued production in
43 the south and east of England will be dependent on the provision of adequate sources of water for
44 irrigation. In addition, harvesting in wetter autumns could also be problematic (Charlton et al., 2010).

45 The main region within England for which water is crucial for agriculture production is the Anglian region
46 where the main use of water is for irrigation, both for the production of cash crops as well as for
47 horticulture. The average abstraction of water (excluding tidal) in the Anglian region for spray irrigation
48 between 2000 and 2012 was 50.5 million m³ accounting for the 59% of the average total water used in
49 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)

50 the Anglian region accounts for the 38% of total licences in England². Irrigation in the East Anglian River
51 Basin Catchment (EARBC) and in the South East of England is mainly concentrated on cash-crop
52 production (potatoes and sugar beet) as well as horticulture and therefore it is considered as a major
53 production input to secure yield and income for the farmers, especially during dry periods. Irrigated
54 production delivers substantial economic benefits not only at the farm gate but also beyond that point
55 since it supports a number of related businesses that provide equipment and farm supplies and are also
56 responsible for the promotion and distribution of production. It can therefore be considered as an
57 important factor for the development of the rural economy in East Anglia (Knox et al., 2009) and other
58 regions of England with horticulture production like the South East, Thames, Humber, South West, etc.
59 river basin catchment areas. The EARBC and England in general may face high pressures in future due
60 to both a) an increase in water abstraction rates for agriculture due to increased water demand and
61 increased number of abstraction licences and b) a decrease in water availability associated with
62 changing weather conditions. The main climate threats are temperature increase and reduced
63 precipitation (Defra, 2009; Environment Agency, 2008, 2011) with direct impacts on the hydrology
64 structure of the area.

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

70 Irrigated agriculture in England has therefore to achieve two goals in order to secure the future growth
71 and the economic sustainability of the sector. The first objective is to maintain and improve productivity
72 in order to meet increasing future food demand (FAO, 2011) but at the same time to preserve the
73 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

74 frequent dry periods in the area may increase the competition for water resources in an already over-
75 abstracted and over-licensed catchment (Knox et al., 2009). The Sustainable Intensification (SI) of
76 agricultural production is promoted as a mechanism that can balance the two objectives and at the
77 same time mitigate any conflicts between these two objectives. More specifically, the SI of agriculture
78 requires farmers to simultaneously increase their yields in order to meet the future demand for food,
79 but also to reduce environmental pressures generated by the production process (Garnett and Godfray,
80 2012).

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

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

101 or customer reasons as the primary reasons (55%) for farmers carrying out management practices for
102 efficient water use in irrigation (Defra, 2011).

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

109 Water demanded for irrigation at a farm level depends on farmers’ decisions on when and which crop
110 to produce, the volume and the frequency of irrigation and also the selection of irrigation method and
111 technology (Marques et al., 2005). It is therefore a decision related to the production technology and
112 the management ability of the farmer. Vico and Porporato (2011), note that there are a number of
113 uncertainties in relation to both the economic and productivity goals of a farmer that increase the
114 complexity of the choice of a sustainable and efficient water management strategy. These uncertainties
115 are related to pests and diseases, temperature extremes, rainfall variability and timing in relation to
116 crop growth stages, crop physiological properties and response to water availability. Further, they are
117 confounded by differences in soil properties that determine water runoff and percolation (English et al.,
118 2002). Among the above, rainfall variability (especially increased frequency of drought periods during
119 the growing season) can significantly impact productivity and profitability (Vico and Porporato, 2011).

120 **1.1. Measuring water use efficiency at a farm level**

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

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

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

134 In the literature there are broadly two approaches used to obtain efficiency estimates at a farm level;
135 parametric techniques (i.e. Stochastic Frontier Analysis (SFA)) and non-parametric techniques (i.e. Data
136 Envelopment Analysis (DEA)). Parametric techniques are used for the specification and estimation of a
137 parametric production function which is representative of the best available technology (Chavas et al.,
138 2005). The advantage of this technique is that it provides the researcher with a robust framework for
139 performing hypothesis testing, and the construction of confidence intervals. However, its drawbacks lie
140 in the *a priori* assumptions in relation to the functional form of the frontier technology and the
141 distribution of the technical inefficiency term, in addition to the results being sensitive to the parametric
142 form chosen (Wadud and White, 2000).

143 Due to the flexibility of DEA, in avoiding a parametric specification of technology and assumptions about
144 the distribution efficiency but at the same time allowing for curvature conditions to be imposed, it is the
145 preferred method for the analysis of technical and specific input (water use) efficiency in the EARBC
146 over SFA. DEA is used to evaluate the performance efficiency of various Decision Making Units (DMU's)
147 which convert multiple inputs into multiple outputs. It is a technique that provides a straightforward
148 approach to measure the gap between each farmer's behaviour from best productive practices, which
149 can be estimated from actual observations of the inputs and outputs of efficient firms (Lansink et al.,
150 2002; Wang, 2010). The production frontier is constructed as a piecewise linear envelopment of the
151 observed data points. This means that the best performing farms are identified as those using the least
152 amounts of inputs to produce their individual levels of output. Linear, or convex, combinations of those
153 best performers constitute the production frontier. The efficiency of the farms is then measured relative
154 to this estimated frontier of best performers (Lilienfeld and Asmild, 2007).

155 Various research projects have used DEA for measuring water use efficiency at a farm level in areas
156 where water use for irrigation is a critical issue in securing economic, social and environmental
157 sustainability like in Mauritania, Tunisia, South Africa and other parts of the world with relative dry
158 climate (Borgia et al., 2013; Chebil et al., 2012; Chemak, 2012; Frija et al., 2009; Lilienfeld and Asmild,
159 2007; Mahdi et al., 2008; Speelman et al., 2008; Veettil et al., 2011; Wang, 2010). The majority has
160 used a sub-vector DEA model to estimate excess water use as proposed by Färe et al. (1994).

161 **1.2. Objectives**

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

176 For the purposes of the analysis, water use efficiency is defined as the ratio of the minimum feasible
177 water use (based on the non-radial notion of input specific technical efficiency (Fang et al., 2013)) to
178 the observed water use at a farm level for irrigation, subject to the available production technology, the
179 observed level of outputs and the use of other inputs (Matthews, 2013). It is therefore an input oriented
180 measure of technical efficiency which allows for a radial reduction of water use at farm level (Wang,
181 2010). This approach allows for a specific input reduction (water) without altering the production output

182 and the quantities of other inputs used. It is emphasised that in this sense, water use efficiency has an
183 economic rather than an engineering meaning (Kaneko et al., 2004; Wang, 2010).

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

191 **1.3. Determinants of efficiency**

192 Water use efficiency in agriculture can be influenced by various factors as they have been identified in
193 the literature. Wang (2010) suggests that age, income, education level, farm size and the different
194 irrigation systems are factors influencing water use efficiency. Moreover, Wang (2010) identified that
195 exclusive water property rights as well as the competitive price mechanism had a strong influence in
196 efficiency. The same structure parameters as above were regressed at a second stage by Mahdi et al.
197 (2008), Lilienfeld and Asmild (2007) and Speelman et al. (2008). The latter, in addition, took into
198 consideration as an influencing parameter the choice of crop, the landownership and the total cultivated
199 area. The same approach was adapted by Wambui (2011) in the assessment of water use efficiency
200 and its influencing parameters in the Naivasha lake basin. Structural and managerial characteristics
201 were also proven to influence the technical performance of farms by Van Passel et al. (2007) who
202 concluded that the same factors as mentioned above as well as the prospect of succession and
203 dependency on subsidies are influencing efficiency.

204 **2. Overview of the study area and data requirements**

205 Data for the empirical application of the model have been obtained from the Farm Business Survey³
206 (FBS) which is a comprehensive and detailed database that provides information on the physical and
207 economic performance of farm businesses in England. The FBS uses a sample of farms that is
208 representative of the national population of farms in terms of farm type, farm size and regional location.
209 The FBS survey is carried out by the Rural Business Research and is the largest and most extensive
210 business survey of farms in England. It is commissioned by the Department for Environment, Food and
211 Rural Affairs (DEFRA) and is also supported by the farming unions. There were in total 8,996 horticultural
212 businesses in England. However, approximately half of these are regarded as being too small for
213 inclusion in the FBS, as they fall below the minimum threshold. The sample size for 2009 cropping year
214 was 212 businesses. Out of those farms, 151 participated in the water use survey of the FBS with an
215 average of 95 ha main crop area and an average of 26 ha irrigated area. Hence, farms with a percentage
216 of irrigated area over main crop area less than 90% were excluded from the sample. This criterion was
217 set in order to ensure that the sample contained only horticulture farms that rely their production on
218 irrigation. A sample of 74 Horticulture Farms was selected from the FBS 2009/2010 database. The
219 majority of the farms are based in EARBC (25 farms) followed by farms based in the catchment area of
220 South East (13 farms), Thames (9 farms), Humber (8 farms), South West (7 farms), Severn (7 farms),
221 North West (3 farms) and Northumbria (2 farms). The average water use for irrigation for the sample
222 is 2,710 m³/ha.

223 In particular the 2009/2010 cropping year could be characterised as a period with a series of events
224 strongly influencing both the area harvested and the growing conditions of crops. The 2009 spring was
225 characterised by generally cool, dry conditions which facilitated agricultural operations and reduced crop
226 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.fbpartnership.co.uk/index.php?id=1528>

227 diseases in sugar beet and potatoes. Sugar beet harvest was disrupted by the exceptionally cold
228 conditions in January 2010 causing also problems for the transport of the product to the market
229 destinations. In regards to irrigation, substantially fewer farmers irrigated crops than held abstraction
230 licences for spray irrigation, due in part to the dry conditions of 2009. In addition, since DEA methods
231 are quite sensitive to the presence of outliers in the data when measuring efficiency (Sexton et al.,
232 1986), eight farms were omitted from the initial sample, being identified as outliers based on the method
233 described in (Wilson, 1993, 2010). These outlier farms would have had a strong influence on the
234 construction of the benchmarking frontier and therefore could influence the results and the
235 interpretation of the efficiency scores. The final number of farms in the research sample was 66. The
236 graphical method of Wilson (1993) is presented in detail on the online appendix of this paper. In total,
237 the sample includes 22 large, 24 medium and 20 small farms as well as 1 very small farm satisfying the
238 need to account for all different farm sizes⁴.

239 The horticulture farming systems⁵ were selected over other agricultural systems mainly because of three
240 reasons 1) their contribution to UK agricultural output (£2,504 million in 2009 and £3,007 million in
241 2013), 2) the demand of supplemented irrigation to secure yield (under drought conditions) and 3)
242 because it is one of the most representative agricultural systems in East Anglia and South East (areas
243 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: $1 < \text{FTE} < 2$, Medium farms: $2 < \text{FTE} < 3$, Large farms: $3 < \text{FTE} < 5$

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).

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

252 **3. Methodology: Data Envelopment Analysis**

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

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

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

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

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

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

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

277 Also, in the above formulation we consider that there is a set of discretionary or variable inputs DI ,
 278 $DI \subset \{1, \dots, J\}$ and a set of non-discretionary inputs NDI , $NDI = \{1, \dots, F\} \setminus DI = \{h \in \{1, \dots, J\} \mid h \notin$
 279 $DI\}$ that cannot be adjusted or are held fixed at least in the short run. The combination of the DI and
 280 NDI variables defines therefore the technology set P:

$$P = \{(x_{DIji}, x_{NDIji}, y_{ri}) \mid x_{DIji} \text{ and } x_{NDIji} \text{ can produce } y_{ri}\} \tag{2}$$

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

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

284

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

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

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

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

291 Where, x_{DIji} is the j^{th} discretionary input for farm i , x_{NDIji} is the j^{th} non-discretionary input for farm i
 292 and y_{ri} is the r^{th} output for farm i , $i = (1, \dots, n)$, $j = (1, \dots, m)$ and $r = (1, \dots, s)$. The optimal value θ
 293 represents the sub-vector efficiency score for each farm and its values lie between 0 and 1. This
 294 efficiency score indicates how much a farm is able to reduce the use of its discretionary inputs (water
 295 use) without decreasing the level of outputs with reference to the best performers or benchmarking
 296 farms in the sample. The first two constraints limit the proportional decrease in both discretionary
 297 (equation-5_(i)) and non-discretionary (equation-5_(ii)) inputs, when θ is minimised in relation to the
 298 input use achieved by the best observed technology. The third constraint ensures that the output
 299 generated by the i^{th} farm is less than that on the frontier. All three constraints ensure that the optimal

300 solution belongs to the production possibility set. The final constraint expressed by the equation $5_{(iv)}$,
 301 called also the convexity constraint, ensures the VRS assumption of the DEA sub-vector model.
 302 Therefore, the non-discretionary inputs can be treated in the DEA model as negative outputs (Bogetoft
 303 and Otto, 2010). The CRS and VRS models differ only in that the former, but not the latter includes the
 304 convexity condition described by equation $5_{(iv)}$ and its constraints in $5_{(v)}$ (Cooper et al., 2007).

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

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

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

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

323 This projected point is a linear combination of the observed data points, with the constraints ensuring
 324 that the projected point cannot lie outside the feasible set. The overall technical efficiency measure of
 325 farm A relative to the frontier is given by the ratio $\theta = OA^0/OA$. In the case of measuring the sub-vector

326 efficiency for input X_1 (water use), then water use (X_1) is reduced while holding X_2 (all the remaining
327 inputs – agricultural crop production costs, area farmed, energy costs, etc.) and output (Gross Margin)
328 constant. In the graph A is projected to A' and sub-vector efficiency is given by the ratio $\theta' = O'A'/O'A$.

329 **3.1. The impact of the size of economies of scale on the productivity of the farm**

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

$$SE = \frac{TE_{CRS}}{TE_{VRS}} \quad (7)$$

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

$$TE_{CRS} = TE_{VRS} * SE \quad (8)$$

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

346 One shortcoming of the measurement of SE is that when $SE < 1$ it is difficult to indicate whether the
347 farm operates in an area of Increasing Returns to Scale (IRS), Decreasing Returns to Scale (DRS) or
348 Constant Returns to Scale (CRS). For that reason a detailed analysis and discussion of the nature of
349 Returns to Scale (RTS) is required. The nature of RTS is determined by the relationship of the proportion
350 of inputs used to produce the output for a farm. Whether IRS, DRS or CRS prevail depends on the

351 relationship between the proportional change of inputs and outputs (Varian H., 2010). This shortcoming
352 can be bypassed if an additional DEA problem with non-increasing returns to scale (NIRS) is imposed.
353 This can easily be achieved by substituting the $\sum_{i=1}^n \lambda^i = 1$ restriction in equation (5) with $\sum_{i=1}^n \lambda^i \leq 1$
354 and then calculating the relevant technical efficiency (TE_{NIRS}). According to Färe et al. (1985), these
355 three estimated frontiers under CRS, VRS, and NIRS can be used to identify the returns to scale
356 characteristics of the technology at any given point. Specifically, a) if $TE_{CRS} = TE_{NIRS} < TE_{VRS}$, the input-
357 oriented projection of the VRS frontier is under increasing returns to scale b) if $TE_{VRS} = TE_{NIRS} > TE_{CRS}$,
358 diminishing returns hold and c) constant returns to scale hold if and only if $SE = 1 = TE_{CRS} = TE_{NIRS} =$
359 TE_{VRS} .

360 **3.2. Econometric estimation of drivers of water use efficiency**

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

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

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

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

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

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

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

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

$$\begin{aligned} 380 \quad WUEff_{it} = & \beta_0 + \beta_1 * RcollSyst_{it} + \beta_2 * InFieldM_{it} + \beta_3 * WatBalCal_{it} + \beta_4 * DecSuppT_{it} + \beta_5 * Recycl_{it} + \beta_6 \\ 381 \quad & * OptIrrigSyst_{it} + \beta_7 * OtherSyst + \beta_8 * Drip_{it} + \beta_9 * Overh_{it} \\ 382 \quad & + \beta_{10} * DripOverh_{it} + \beta_{11} * TrickOverh_{it} + \beta_{12} * DripTrick_{it} + \beta_{13} * DripTrickOver_{it} + \varepsilon_{it} \end{aligned}$$

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

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

403 The significance of the Simar and Wilson (2007) double bootstrap procedure derives from the bias
404 corrected efficiency estimation of θ' (estimated by expression (5)). These estimates are used as

405 parameters in a truncated regression model. The selection of the model was based on the fact that the
406 outcome variable is restricted to a truncated sample of a distribution. Since the dependent variable can
407 take values between zero and one, we have a left truncation of the sample ($0 \leq$ biased corrected water
408 use efficiency). It must be noted that a censored model (e.g. Tobit) would not have been appropriate
409 in this case since water use efficiency data have the characteristics of truncated data – limited in the
410 sample of interest. Furthermore, according to Simar and Wilson (2007) and Banker and Natarajan
411 (2008) Tobit estimation in the second stage yields biased and inconsistent estimators. The main reason
412 for the selection of the truncated model by Simar and Wilson (2007) is that the true efficiency estimates
413 are unobserved and are replaced with DEA estimates of efficiency. A detailed presentation of the double
414 bootstrapped procedure and the Algorithm 2 used in this paper is available in Simar and Wilson (2007)
415 and also on the online appendix of the paper.

416 **4. Results**

417 The estimated mean of technical efficiency under the two different assumptions of VRS (PTE) and CRS
418 (OTE) for the sample of irrigating horticulture farms was 0.85 (STD=0.20) and 0.74 (STD=0.28)
419 respectively. This implies that the irrigating farms in the sample could on average reduce their inputs
420 by 15% without any size adjustments (PTE is considered) and by 26% when size adjustments are made
421 (OTE is considered), maintaining in both cases the same level of output. Table 3 presents statistical
422 information and the distribution of PTE and OTE for the sample. The mean SE is 0.86 (STD=0.22) with
423 40% of the farms operating at their optimal scale (SE=1).

424 The mean sub-vector efficiency is 0.51 (STD=0.44) under the assumption of CRS (OTE), indicating that
425 the observed value of outputs (Gross Margin) could have been maintained by keeping the level of other
426 inputs constant whilst reducing water requirements by 49%. In addition, when VRS (PTE) are assumed
427 the mean sub-vector efficiency for the horticulture farms in the sample is 0.65 (STD=0.41) indicating a
428 reduction in water requirements by 35%. Table 4 presents the relationship between technical efficiency
429 estimated by the conventional model (all inputs are discretionary) and the sub-vector model (water use
430 is a discretionary input and the remaining inputs are considered as non-discretionary). Savings in water
431 use were estimated through expression (6) by taking into consideration also the difference in technical

432 and sub-vector efficiency estimates. In the case of medium and small size farms, water savings are
433 estimated to 533 m³/ha in average, while for large size farms this can be more than 1000 m³/ha.

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

445 **4.1. The econometric estimation of water use efficiency determinants**

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

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

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

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

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

478 **5. Discussion and implications**

479 The increased frequency of extreme weather phenomena (drought and flood periods) in the future for
480 the UK will result to a higher risk with regards to securing yield and farm income. This, in addition to
481 increased food demand, has raised the need for agricultural production systems to adapt in a challenging
482 and insecure environment. Agriculture in the EARBC and also in the South East of England is vulnerable
483 to water shortages due to the increasing risk of drought and over abstraction of water resources. In
484 addition, considering the substantial financial benefits for irrigation, especially for high value crops and

485 vegetables, any distortions in the supply of water for irrigation will have a significant impact on farmers'
486 income. Therefore the efficient use of water resources becomes a joined priority within the framework
487 of SI of agriculture which requires a sustainable and efficient management of natural resources.

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

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

503 Around 36% of the farms in the sample are abstracting water directly from bore holes, river streams,
504 ponds, lakes and reservoirs. Irrigation water demand for the remaining 70% of the farms is supplied by
505 water companies. The average cost of water supplied for irrigation by water companies is £2.59/ m³
506 (STD=5.55, Trimmed Median =£1.13). According to the results presented in Table 4, the average
507 potential savings in cost of water used for irrigation that can be achieved is 649 £/farm in a year. Hence,
508 the adoption of efficient water recycling systems as these are identified by the results of the second
509 stage regression analysis of this paper and the use of a decision for irrigation support tool can potentially
510 reduce significantly input costs and also improve production efficiency. The installation and use of a
511 recycling water systems can increase water use efficiency score by 0.26.

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

520 In order to renew their abstraction licences farmers are required to demonstrate efficient use of water
521 resources to the regulator (Environment Agency, 2013). The results from the sub-vector model confirm
522 that almost half of the farms (53%) in England are on the frontier and hence avoid any excess in water
523 use when compared with peer farms in the sample. Knox et al. (2012) refers to the "Save water, save
524 money⁶" booklet produced in 2007 and distributed to 2500 farmers across England to promote the
525 "pathway to efficiency". The main components of the pathway include that farmers understand their
526 system of production, make efforts to optimise the use of their irrigation systems, ensure appropriate
527 soil and water management and demonstrate best practices that have proved over time to lead to more
528 efficient irrigation (Knox et al., 2012).

529 The profile of the best performing irrigating farms in our sample resulting from the study of the farms
530 on the frontier can be used as a good practice example to promote water use efficiency in England. The
531 installation and use of a trickle/drip/spray lines irrigation system as it was shown by the results of the
532 second stage analysis can increase water use efficiency when compared to other irrigation systems used
533 by the sample. The spray type trickle irrigation systems have the advantage that are less likely to clog
534 when compared to subsurface and drip systems, can improve crop yields and reduce water use and
535 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>

536 category of micro-irrigation systems that include various low rate emission devices such as drip
537 irrigation, subsurface irrigation, bubbler irrigation and many other. However, on the other hand the use
538 of drip irrigation systems by the farms on the sample had a negative impact on water use efficiency.

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

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

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

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

561 Furthermore, as it was shown from the regression analysis the set of water use efficiency irrigation
562 management practices and systems with a positive and statistically significant impact on water use

563 efficiency (recycling water, decision support tool and the use of trickle/drip/spray lines irrigation
564 systems) can be an effective strategy to reduce runoff and significantly contribute to the reduction of
565 diffuse pollution which is in line to the findings of the MOPS2 project (Deasy et al., 2010). Such practices
566 will improve water quality and also enable UK agriculture to meet the requirements of the EU water
567 framework directive.

568 **6. Conclusions**

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

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

585 From a policy perspective, the current water abstraction regulation in the UK is under reform. The main
586 pillars of the reform are based on the need to face challenges in water availability due to changing
587 weather conditions, the increased demand for water from growing population and the need to enable
588 trading of water rights (Defra, 2013). Our results suggest that the new legislation should incentivise
589 farmers to improve management practices for efficient water for irrigation and also improve water

590 storage at farm level through rain harvesting and on farm reservoirs. Furthermore, it is essential that
591 any reform accounts for the importance of supplementary irrigation for cash crops (potatoes, sugar
592 beet) and the need to secure yield. Any restriction on water abstraction during the growth period due
593 to water shortages or drought conditions would result to failure in meeting quality standards and
594 consequently income loss to farmers. Therefore, it is important that the new regime considers the
595 economic significance off irrigated agriculture not only for the farming systems but also for the local
596 jobs and local economies.

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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 (m³/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

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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	

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

Irrigating horticulture farms				
Efficiency level (%)	Technical efficiency		Water Use Efficiency	
	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	

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

FarmID	Water Use (m³/ha)	Technical Efficiency VRS	Water Use Efficiency VRS	Water Savings (m³/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

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764 **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

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770 **Table 6: Truncated regression. The dependent variable is the vector of the reciprocal of DEA estimate**
 771 **(distance function), estimated in the input-oriented sub-vector DEA model with variable returns of**
 772 **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

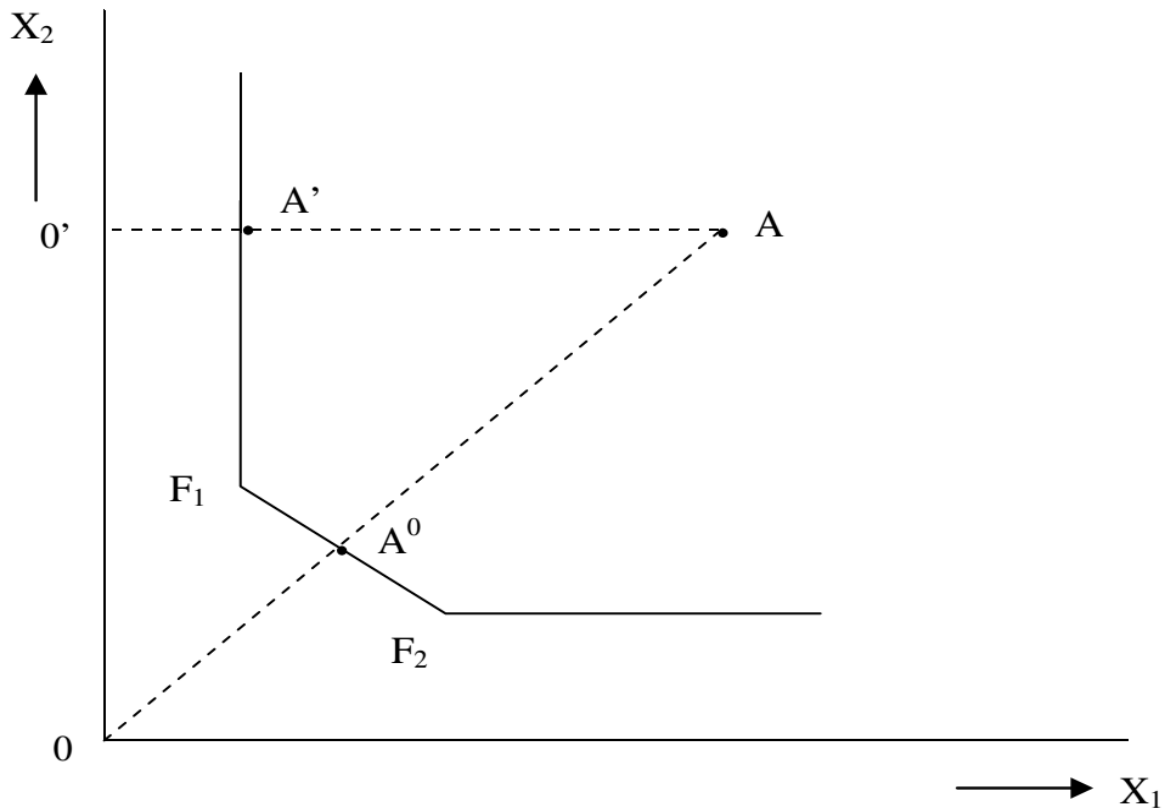
773 Signif. codes: '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 1 – No of Bootstraps 2000

774 Log likelihood=-6.21

775 Wald $\chi^2(15) = 40.17$, Prob > $\chi^2 = 0.00$

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780 **Figure 1: Graphical representation of the measurement of technical efficiency and sub-vector**
 781 **efficiency using DEA for an example with two inputs and one output (adapted from Lansink et al.**
 782 **(2002))**

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