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On the Opportunity Cost of Crop Diversification

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Abstract

Distance functions are increasingly being augmented, with environmental goods treated as conventional outputs. A common approach to evaluate the opportunity cost of providing an environmental good is the exploitation of the distance function's dual relationship to the value function. This implies that the opportunity cost is assumed to be non-negative. This approach also requires a convex technology set. Focusing on crop diversification for a balanced sample of 44 cereal farms in the East of England for the years 2007-2013, this paper develops a novel opportunity cost measure that does not depend on these strong assumptions. We find that the opportunity cost of crop diversification is negative for most farms.

Keywords biodiversity, CAP greening measures, Shannon index, non-convexity, shadow price, duality, crop diversification

JEL code D22, D24, D92, Q12, Q51

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21 **1. Introduction**

22 Agriculture not only provides economic outputs, but also generates externalities including
23 environmental goods (*e.g.*, landscape conservation and habitat for birds) and ‘bads’ (*e.g.*,
24 nitrogen and phosphorus surplus due to fertiliser use). Environmental goods and bads are non-
25 marketed, and may call for government intervention to deal with or internalise these external
26 benefits and costs to align consumers’ and producers’ interests (Areal, Tiffin et al., 2012). A
27 large body of economic literature assesses the trade-off between production and externalities.
28 Externalities have commonly been implemented in a distance function framework, to estimate
29 environmental efficiency and productivity measures. The shadow price of an externality can be
30 computed by exploiting the distance function’s dual relationship to the value function. Knowing
31 the shadow price of an externality is useful for policy makers, who may set up schemes to
32 compensate for the potential financial losses incurred by the farmers.

33 Studies originally focused on environmental bads. Examples in the agricultural sector include
34 nitrogen surplus (Piot-Lepetit and Vermersch, 1998; Reinhard, Lovell et al., 1999; Piot-Lepetit
35 and Le Moing, 2007), phosphorus surplus (Reinhard, Lovell et al., 2000; Coelli, Lauwers et al.,
36 2007), pesticide pollution (Oude Lansink and Silva, 2004; Chambers, Serra et al., 2014; Serra,
37 Chambers et al., 2014) and greenhouse gas emission (Oude Lansink and Silva, 2003; Dakpo,
38 Jeanneaux et al., 2017).

39 The literature has increasingly identified an interest in augmenting distance functions with
40 environmental goods. To the best of our knowledge, Färe, Grosskopf et al. (2001) are the first
41 to adopt this approach, focussing on non-marketed characteristics of conservation land in the
42 United States. Other studies extend the distance function with the extent of wetland and interior
43 forest (Macpherson, Principe et al., 2010), six key indicators of biotic integrity of watershed
44 data (Bellenger and Herlihy, 2009; Bellenger and Herlihy, 2010), the extent of permanent
45 grassland (Areal, Tiffin et al., 2012), cultural services, biodiversity, carbon sequestration and
46 the extent of arable and grassland (Ruijs, Wossink et al., 2013; Ruijs, Kortelainen et al., 2017),
47 the Shannon index for crop diversity (Sipiläinen and Huhtala, 2013), and wetland quality
48 (Bostian and Herlihy, 2014). Färe, Grosskopf et al. (2001), Bellenger and Herlihy (2010), Ruijs,
49 Wossink et al. (2013), Sipiläinen and Huhtala (2013), Bostian and Herlihy (2014) and Ruijs,
50 Kortelainen et al. (2017) compute the shadow price of their environmental goods by exploiting
51 the output distance function’s dual relationship to the revenue function.

52 These studies’ distance function approach has two important limitations, which can lead to an
53 incorrect assessment of the opportunity cost of the considered environmental good. First, it is

54 assumed that an environmental good can be treated as a conventional, strongly disposable
55 output and that its shadow price is consequently always non-negative. Second, it is necessary
56 to assume that the augmented environmental technology set is convex, to ensure that the
57 distance function's dual relationship to the value function holds.

58 Both assumptions are very strong. The strong disposability assumption implies that the
59 provision of an environmental good is assumed to be non-increasing for increases in the output
60 level. However, several contributions argue that some environmental goods are complementary
61 to conventional production for lower levels of the environmental good, and competitive for
62 higher levels (Harvey, 2003; Hodge, 2008). This means that the shadow price of an
63 environmental good could also be negative. Such a complementary-competitive relationship is
64 hypothesized for *inter alia* the environmental quality of grassland and livestock production
65 (Vatn, 2002), pollinator habitat and crop production (Wossink and Swinton, 2007), and the
66 entire ecosystem on the farm and total agricultural production (Hodge, 2000). The strong
67 disposability assumption also implies that the provision of an environmental good is assumed
68 to be non-decreasing for increases in the input level. As shadow-pricing of environmental goods
69 inherently focuses on the trade-off between the environmental good and the conventional
70 output, this has generally been left undiscussed by the literature. However, there is no
71 theoretical reason to assume this *a priori*. Ruijs, Wossink et al. (2013) and Ruijs, Kortelainen
72 et al. (2017) seem to be the only authors that check the transformation function empirically and
73 confirm the theorised relationships. Nonetheless, this remains a contested assumption for which
74 the theoretical basis is lacking and the evidence is scarce. We believe that this assumption is
75 especially problematic for inputs that increase the provision of environmental bads such as
76 pesticides and fertilisers.

77 More and more studies argue that the environmental technology set is non-convex (Di Falco
78 and Chavas, 2009; Chavas and Di Falco, 2012). The convexity assumption is invoked for
79 analytical rather than theoretical reasons (Pope and Johnson, 2013). Again, Ruijs, Wossink et
80 al. (2013) and Ruijs, Kortelainen et al. (2017) seem to be the only authors that empirically test
81 the convexity assumption. They do not find evidence of convexity. This implies that their
82 resulting opportunity costs do not maximise benefits and should not be used to design a pricing
83 mechanism.

84 We focus on the Shannon index for crop diversity. This index was also the focus for Sipiläinen
85 and Huhtala (2013), who computed its shadow price using the dual relationship of the distance
86 function to the revenue function. Crop diversity has been shown to be linked with *inter alia*
87 long-term stability of the carbon stock in the soil (Henry, Tittonell et al., 2009), improved

88 nutrient balance (Pimentel, Hepperly et al., 2005) and landscape diversity (Westbury, Park et
89 al., 2011). In the context of crop production, it measures the crop diversity by representing the
90 number of crop types and evenness of the area covered by the crops. Considering the number
91 of crop types as well as evenness, the Shannon index for crop diversity is an essential
92 determinant of sustainable food supply (Aguilar, Gramig et al., 2015). From an ecological
93 perspective, it is thus important to increase the Shannon index for crop diversity. Various
94 studies in the economics literature use the Shannon index for crop diversity as an environmental
95 good (e.g., Weitzman, 2000; Di Falco and Chavas, 2008; Sipiläinen and Huhtala, 2013).

96 Correct assessment of the opportunity cost of crop diversification is also relevant given the
97 ‘Green Direct Payment’ measure introduced recently in 2015 by the European Common
98 Agricultural Policy (CAP), which holds for all member states of the European Union. This
99 measure links thirty percent of the direct payments to the provision of environmental goods.
100 One condition for receipt of these payments is the ‘2 or 3 crop rule’ (European Parliament,
101 2013). This regulation imposes minimum requirements on the number of crops and their
102 proportional cover, which is conceptually in line with the Shannon index for crop diversity.
103 Farms of 10-30 ha should grow at least two crops, with the main crop covering at most 75% of
104 the arable land. Farms larger than 30 ha should grow at least three crops, with the main crop
105 covering at most 75% of the arable land, and two crops covering a maximum of 95% of the
106 arable land. In summary, the Shannon index for crop diversity is relevant in terms of both
107 ecological benefits and policy.

108 Given the theoretical concerns of shadow-pricing environmental goods using the distance
109 function approach, we compute the opportunity cost of crop diversification in a novel way. Our
110 proposed method is conceptually straightforward. If we use a credible assumption of economic
111 behaviour and its corresponding Shannon index for crop diversity, we can accurately compute
112 the opportunity cost of crop diversification. Such an approach separates the environmental good
113 from the production technology and does not necessarily require a convex technology set, thus
114 overcoming the axiomatic problems associated with shadow-pricing using the distance function
115 approach.

116 We operationalise our proposal using recent methodological developments in the literature.
117 Cherchye, De Rock et al. (2017) show how one can take into account the output-specific
118 character of inputs and the extent to which reallocation of these inputs over outputs can increase
119 efficiency. We adapt their input distance function framework to Ang and Oude Lansink
120 (2017)’s dynamic profit-maximisation framework and focus on the optimal reallocation of
121 output-specific land use. Using a nonparametric model, we assess the extent to which

122 reallocation of land use can increase current-value profit. We express the opportunity cost of
 123 increasing the Shannon index for crop diversity in terms of foregone current-value profit. Doing
 124 so allows us to calculate the opportunity cost of crop diversification in a way that avoids
 125 implementing the environmental good in the technology set and thus imposes less stringent
 126 assumptions on the axiomatic properties of the technology set. Our proposed approach is
 127 consistent with the behavioural assumption of dynamic profit-maximisation. Finally, we are
 128 able to assess the extent to which farmers would have complied with the CAP's novel '2 or 3
 129 crop rule' should they have optimally reallocated their land use. The application focuses on a
 130 balanced sample of 44 cereal farms in the East of England for the years 2007-2013.
 131 The remainder of this paper is structured as follows. The next section explains our method. This
 132 is followed by a description of the data. The results are presented and discussed in the
 133 subsequent sections. The final section concludes.

134 **2. Method**

135 Following Ang and Oude Lansink (2017), farms are faced with a dynamic, intertemporal profit-
 136 maximisation problem where they are price takers in competitive input, output and capital
 137 markets, and have identical, static expectations on the discount and depreciation rates. It is
 138 assumed that the farms maximise the discounted flow of profits over time at any base time
 139 period, while being restricted by the adjustment-cost technology. The latter assumption
 140 coincides with the perspective that farms cannot instantaneously adjust quasi-fixed inputs to
 141 their long-term optimal levels and investments are coupled with adjustment costs (Silva and
 142 Stefanou, 2003; Silva, Oude Lansink et al., 2015). The (variable) intertemporal profit-
 143 maximisation problem is (Ang and Oude Lansink, 2017):

$$144 \quad (1) \quad W(p, K_t, w, c) = \max_{\{y(\cdot), x(\cdot), I(\cdot)\}} e^{-r(s-t)} \int_t^{+\infty} [p'y(s) - w'x(s)] ds$$

145 *s.t.*

$$146 \quad (2) \quad \frac{dK(s)}{dt} = I(s) - \delta K(s) \text{ with } K(t) = K_t$$

$$147 \quad (3) \quad \vec{D}_T(y(s), x(s), I(s), K(s), G(s), L(s); g_y, g_x, g_I) \geq 0 \text{ with } s \in [0, +\infty[$$

148 where $W(\cdot)$ is the current value form of dynamic profit-maximisation, $y \in \mathbb{R}_+^M$ is the crop
 149 output vector, $x \in \mathbb{R}_+^N$ is the variable input vector, $K_t \in \mathbb{R}_+^F$ is the initial capital stock vector,
 150 $I \in \mathbb{R}_+^F$ is the investment vector, $L \in \mathbb{R}_+^M$ is the crop-specific land vector, $G \in \mathbb{R}_+^Z$ is the vector
 151 of non-reallocatable fixed factors, $p \in \mathbb{R}_+^M$ is the vector of output prices, $w \in \mathbb{R}_+^N$ is the vector
 152 of input prices, $r > 0$ is the rental rate, δ is a diagonal $F \times F$ matrix of depreciation rates $\delta_f >$

153 $0, f, \dots, F$ and $\vec{D}_T(\cdot)$ is the dynamic directional distance function with the corresponding
 154 directional vector in terms of outputs, inputs and investments (g_y, g_x, g_I) . Eqs. (2) and (3)
 155 denote the equation of motion and the dynamic technology, respectively. For a full
 156 characterization of the dynamic directional distance function (extended with the net investment
 157 vector), we refer to the appendix of Ang and Oude Lansink (2017).

158 In line with Cherchye, De Rock et al. (2013) and Cherchye, De Rock et al. (2017), we make a
 159 distinction between *joint* and *output-specific* inputs. A joint input cannot be allocated to one
 160 specific output and is thus needed for the production of multiple outputs. An output-specific
 161 input is allocated to one particular output. Variable and fixed non-reallocatable inputs are joint
 162 inputs. Land is our considered output-specific input. This approach is a more realistic
 163 representation of the production technology and allows for increased detection of non-
 164 maximising farms.

165 Omitting the time indicators for simplicity, the current-value formulation of Eqs. (1) – (3) is
 166 (Ang and Oude Lansink, 2017):

$$167 \quad (4) \quad rW(p, K, w, c) = \max_{\{y, x, I\}} \{p'y - w'x + W_K(p, K, w, c)'(I - \delta'K)\}$$

168 *s.t.*

$$169 \quad (5) \quad \vec{D}_T(y, x, I, K, G, L; g_y, g_x, g_I) \geq 0$$

170 where $W_K(\cdot)$ is the shadow value of capital. $W_K(\cdot)$ indicates the increase in current-value profit
 171 for a one-unit increase in net investment. It is an implicit, endogenous variable. Nonetheless, as
 172 all input prices and output prices are known, we can obtain farm-specific values for $W_K(\cdot)$ by
 173 solving a minimax problem following Kuosmanen, Kortelainen et al. (2010) (see Appendix A).
 174 In what follows, we operationalise Eqs. (4) – (5) using a nonparametric approach. We note that
 175 the empirical analyst may also opt for a parametric approach, which can be more convenient
 176 for statistical comparisons. However, this requires a specification of the functional form, which
 177 is prone to violations of regularity conditions. The nonparametric approach does not violate any
 178 regularity conditions by construction, not requiring any specification of a functional form. In
 179 addition to these general remarks, a nonparametric approach is very suitable for this application
 180 in particular. First, our paper focuses on computing farm-specific opportunity costs of crop
 181 diversification rather than coefficients or elasticities. Second, there are several recent
 182 methodological advances in the nonparametric literature, apt for this application. By
 183 specifically characterising the inputs as output-specific or joint, and allowing for reallocation

184 possibilities of output-specific inputs (in our case land use), one can model the production
185 process on the farm in a detailed way.

186 We assume that the production technology satisfies the standard properties of closedness,
187 boundedness, strong disposability of inputs, outputs and investments, and variable returns to
188 scale (see e.g. Färe and Grosskopf, 2005). The benchmark scenario (A) is solved for each farm

189 $j \in \mathbb{R}_+^J$:

$$190 \quad (A) \quad rW(p, w, K, c)^{(1)} = \max_{\{y, x, I, \gamma\}} \{p'y - w'x + W_K(\cdot)'(I - \delta K)\}$$

191 *s.t.*

$$192 \quad (A.1) \quad y_m \leq \sum_{j=1}^J \gamma_m^j y_m^j, m = 1, \dots, M$$

$$193 \quad (A.2) \quad \sum_{j=1}^J \gamma_m^j x^j \leq x_n, m = 1, \dots, M, n = 1, \dots, N$$

$$194 \quad (A.3) \quad (I_f - \delta_f K_f) \leq \sum_{j=1}^J \gamma_m^j (I_f^j - \delta_f K_f^j), m = 1, \dots, M, f = 1, \dots, F$$

$$195 \quad (A.4) \quad \sum_{j=1}^J \gamma_m^j G^j \leq G_z, m = 1, \dots, M, z = 1, \dots, Z$$

$$196 \quad (A.5) \quad \sum_{j=1}^J \gamma_m^j L_m^j \leq L_m, m = 1, \dots, M$$

$$197 \quad (A.6) \quad \sum_{j=1}^J \gamma_m^j = 1, m = 1, \dots, M$$

$$198 \quad (A.7) \quad \gamma_m^j \geq 0, m = 1, \dots, M, j = 1, \dots, J$$

199 where $\gamma_m^j \in \mathbb{R}_+^M$ are output-specific intensity weights. (A.1), (A.2), (A.3), (A.4) and (A.5)
200 impose strong disposability on the inputs, outputs, net investments, non-reallocatable fixed
201 inputs and reallocatable fixed inputs. (A.6) imposes variable-returns-to-scale. (A.7) ensures
202 non-negativity of the intensity weights. The fixed factors are not included in the objective
203 function, but affect current-value profit through the intensity weights γ_m^j in the constraints.

204 Following Färe, Grabowski et al. (1997), Ang and Kerstens (2016) and Cherchye, De Rock et
205 al. (2015); Cherchye, De Rock et al. (2017), the preceding intertemporal profit-maximisation
206 problem can also be adapted to programme (B) where land use L_m is optimally reallocated
207 among M crops for each farm $j \in \mathbb{R}_+^J$:

$$208 \quad (B) \quad rW(p, w, K, c)^{(2)} = \max_{\{y, x, I, L_m^*, \gamma\}} \{p'y - w'x + W_K(\cdot)'(I - \delta K)\}$$

209 *s.t.*

$$210 \quad (B.1) \quad y_m \leq \sum_{j=1}^J \gamma_m^j y_m^j, m = 1, \dots, M$$

$$211 \quad (B.2) \quad \sum_{j=1}^J \gamma_m^j x^j \leq x_n, m = 1, \dots, M, n = 1, \dots, N$$

$$212 \quad (B.3) \quad (I_f - \delta_f K_f) \leq \sum_{j=1}^J \gamma_m^j (I_f^j - \delta_f K_f^j), m = 1, \dots, M, f = 1, \dots, F$$

213 (B.4) $\sum_{j=1}^J \gamma_m^j G^j \leq G_z, m = 1, \dots, M, z = 1, \dots, Z$

214 (B.5) $\sum_{j=1}^J \gamma_m^j L_m^j \leq L_m^*, m = 1, \dots, M$

215 (B.6) $\bar{L} = \sum_{m=1}^M L_m^*, m = 1, \dots, M$

216 (B.7) $\sum_{j=1}^J \gamma_m^j = 1, m = 1, \dots, M$

217 (B.8) $\gamma_m^j \geq 0, m = 1, \dots, M, j = 1, \dots, J$

218 (B.1), (B.2), (B.3), (B.4), (B.7) and (B.8) are equivalent to (A.1), (A.2), (A.3), (A.4), (A.6) and
 219 (A.7), respectively. Output-specific land use is endogenised and is thus an explicit choice
 220 variable L_m^* in constraint (B.5). Constraint (B.6) ensures that the sum of the optimal land uses
 221 is equal to the total land area \bar{L} .

222 Programmes (A) and (B) are linear and thus follow the Data Envelopment Analysis (DEA)
 223 approach. DEA assumes convexity of the technology set, as the frontier consists of convex
 224 combinations of resource allocations of dominating peers, resulting in a piecewise linear
 225 frontier. The convexity assumption is contested less for a production technology with only
 226 conventional inputs and outputs (as in problems (A) and (B)) than for a production technology
 227 augmented with environmental goods or bads (as is commonly done in the literature to compute
 228 environmental efficiency and productivity measures and corresponding shadow prices).
 229 However, this assumption may still be strong in the agricultural context, where various types
 230 of capital equipment are non-divisible (Ang and Kerstens, 2017). Being the main approach in
 231 the economics literature, our paper chiefly focuses on the DEA models. Nonetheless, it is
 232 important to point out that convexity of the technology set is *not* a *necessary* condition for our
 233 dynamic profit-maximisation problems. Varian (1984) and Kuosmanen (2003) show that static
 234 profit maximisation does not require convexity of the technology set. The profit-maximising
 235 resource allocations subject to a non-convex technology set can be computed using the Free
 236 Disposal Hull (FDH) method (Briec, Kerstens et al., 2004). Adapting this reasoning from a
 237 static to a dynamic context, we run such FDH models as a robustness check for non-convexity
 238 of the technology set. The FDH models are similar to the DEA models, being the solutions to
 239 programmes (A) and (B), but with binary intensity variables (i.e. $\gamma_m^j \in [0,1]$). This adjustment
 240 results in mixed-integer programmes by which the dynamic profit-maximising resource
 241 allocation is determined by the resource allocation of only one dominating peer.

242 The gain in current-value profit from optimally reallocating land use is:

243 (6) $\Delta rW(.) = rW(.)^{(2)} - rW(.)^{(1)}$ where $\Delta rW(.) \geq 0$

244 The Shannon index for crop diversity $S(L_m, G_{fallow})$ is the environmental good considered in
 245 our analysis. It is a function of output-specific land use L_m and fallow land G_{fallow} :

$$246 \quad (7) \quad S(L_m, G_{fallow}) = -\sum_{m=1}^M \left[\frac{L_m}{L+G_{fallow}} * \ln \frac{L_m}{L+G_{fallow}} \right] - \frac{G_{fallow}}{L+G_{fallow}} * \ln \frac{G_{fallow}}{L+G_{fallow}}$$

247 In line with the CAP's '2 or 3 crop rule', an area left fallow is counted as crop land use.
 248 Programme (B) seeks for the land allocation under dynamic profit maximisation. We are able
 249 to compute the Shannon index for crop diversity associated with the current allocation $S(.)^{(1)}$,
 250 on the one hand, and the land allocation under dynamic profit maximisation $S(.)^{(2)}$, on the
 251 other. We define the change in the Shannon index for crop diversity due to optimal reallocation
 252 of land use as:

$$253 \quad (8) \quad \Delta S(.) = S(.)^{(2)} - S(.)^{(1)} \text{ where } \Delta S(.) \leq 0$$

254 Finally, we assess the trade-off between current-value profit and the Shannon index by the ratio
 255 of Eq. (6) to Eq. (8). In line with Sipiläinen and Huhtala (2013), we normalise by total land
 256 area:

$$257 \quad (9) \quad \alpha = \frac{-\Delta rW(.) / \Delta S(.)}{10 * (L + G_{fallow})}$$

258 where α is the opportunity cost of the Shannon index as it measures the foregone current-value
 259 profit of increasing the Shannon index by 0.1 per unit of land. A positive (negative) α indicates
 260 that greater crop diversity decreases (increases) current-value profit. As for shadow pricing by
 261 the distance function approach, it indicates a willingness to accept (pay) to increase the Shannon
 262 index by 0.1 per unit of land and is expressed in £ per hectare.

263 A few comments are in order here. The Shannon index for crop diversity increases with the
 264 number of crops and evenness of the area covered by the crops. For a given number of crops, a
 265 farm can maximise its Shannon index by using an even distribution of crop areas. Although an
 266 increase in the Shannon index is generally beneficial in ecological terms, prudence is required
 267 in its interpretation. First, being an integrative measure, some information inevitably becomes
 268 masked. The Shannon index does not provide information about the exact crop shares. This is
 269 particularly relevant for the optimal crop shares under dynamic profit maximisation, where
 270 more profitable products (e.g. barley) can be more difficult to sell on the market or constrained
 271 by limitations on crop rotation. We therefore also discuss the change in land use corresponding
 272 to the optimal change in the Shannon index for crop diversity. Second, the Shannon index is
 273 sensitive to scale. A larger area leads in general to a higher species richness and as a result a
 274 higher Shannon index for crop diversity. Following Sipiläinen and Huhtala (2013), one may

275 choose between an ecologically meaningful scale and an economically meaningful scale. In line
276 with their study, our application opts for the latter, as we are interested in computing farm-
277 specific opportunity costs of crop diversification. The farm level is also the relevant scale in the
278 ‘2 or 3 crop rule’ recently introduced by the CAP.

279 By not implementing an environmental good in the production technology, we avoid making
280 questionable assumptions about the production technology and do not predetermine the sign of
281 the opportunity cost. Our approach does not depend on (1) a non-negative relationship between
282 input use and production of the environmental good, (2) a non-negative trade-off between
283 conventional production and production of the environmental good and (3) convexity of the
284 production technology.

285 The interpretation of the opportunity cost is not exactly the same as the shadow price obtained
286 by exploiting duality. Shadow pricing in the augmented distance function framework is
287 essentially a *marginal* concept which relies on convexity of the environmental technology set.
288 Eq. (9) shows that α should be interpreted as the *average* foregone current-value profit of
289 increasing the Shannon index by 0.1 unit. Our approach is somewhat similar to that of Coelli,
290 Lauwers et al. (2007), who avoid implementing the environmental “bad” (pollutant) in the
291 production technology. They construct “shadow cost estimates” (p. 11) as opportunity costs by
292 calculating the ratio of the difference between costs under minimised pollution and minimised
293 costs, to the difference between minimised pollution and pollution under minimised costs.
294 Throughout this paper, we use the term “opportunity cost” rather than “shadow price” or
295 “shadow cost”, as the latter terms may have the connotation of differentiability of the
296 technology set.

297 **3. Data**

298 We use data from the Farm Business Survey (FBS) dataset for the years 2007-2013. The FBS
299 dataset provides farm-level information on economic and physical characteristics for a large
300 sample of English and Welsh farms. We distinguish eight marketable crop outputs (wheat,
301 barley, oats, beans, peas, potatoes and sugar beet, and ‘other outputs’²), eight variable inputs
302 (seed and planting stock, fertilizer, crop protection, electricity, heating fuel, external labour,
303 management and ‘other variable inputs’), two quasi-fixed inputs (buildings and machinery),
304 one fixed output-specific input that can be reallocated (output-specific land) and two fixed non-

² The ‘other outputs’ category consists of outputs that cannot be counted as separate crop types following the CAP’s ‘2 or 3 crop rule’. Although its corresponding land use is assumed to be reallocatable, it does not enter the calculation of the Shannon index for crop diversity.

305 reallocatable inputs (residual land and family labour). Hired labour and management are
306 expressed in annual working hours. Using price indexes obtained from the EUROSTAT (2015)
307 database, we express the prices of crop outputs, the remaining variable inputs and the
308 investments in quasi-fixed inputs in constant 2007 £. Implicit aggregated quantities are
309 computed for ‘other outputs’ by using Törnqvist price indexes. All outputs include subsidies,
310 but exclude direct payments. The historical depreciation of quasi-fixed inputs is obtained
311 directly from the FBS dataset and also expressed in constant 2007 £. (Residual) land and family
312 labour are measured respectively in hectares and annual working hours. Variable inputs and
313 fixed non-reallocatable inputs are joint inputs. Note that some variable inputs (*e.g.*, purchased
314 seeds for wheat production) could in theory be output-specific, but that such a specification is
315 not possible due to a lack of data. As residual land contains permanent grassland and other
316 herbaceous forage and fallow land, it improves the nutrient cycling in the soil and benefits the
317 overall production of the marketable outputs. Therefore, these land inputs are also assumed to
318 be joint.

319 We only consider specialised crop farms in the East of England that do not produce any
320 livestock during the total time period, to obtain a homogenous sample. The FBS rotates the
321 sample in such a way that every farm stays in the sample for five to seven years on average.
322 We use a balanced dataset of 44 observations per year for a period of seven years to maximise
323 the number of analysed years. Table 1 shows the summary statistics of the dataset.

324 INSERT TABLE 1 AROUND HERE

325 **4. Results**

326 This section is structured as follows. First, we show the main results, where we show the
327 maximum current-value profits obtained using DEA problems (A) and (B), the corresponding
328 Shannon indices and the implied opportunity costs of crop diversification. Then, we conduct
329 several robustness checks to examine the validity of our main results. This section ends with a
330 comparison to the opportunity costs obtained employing Sipiläinen and Huhtala (2013)’s
331 approach, which per usual exploits the distance function’s dual relationship to the value
332 function.

333 *4.1. Main Results*

334 DEA problems (A) and (B) are run for each farm in the sample in each year. This procedure
335 controls for shifts of the frontier in time due to technical progress and fluctuating weather
336 conditions. We report the main results in Tables 2-4 and Figure 1. The monetary values are
337 expressed in constant 2007 £ in what follows.

338 Table 2 shows the actual and maximum current-value profit and corresponding Shannon indices
339 for crop diversity for DEA problems (A) and (B). The actual current-value profit is on average
340 £ 123,900 for all years considered. There is substantial heterogeneity per year, indicating that
341 fluctuating weather conditions play an essential role: while the actual current-value profit
342 reaches on average £ 210,096 in 2012, it is on average only – £ 38,429 in 2009. Assuming that
343 the actual land allocation is fixed, the maximum current-value profit is on average £ 157,407
344 for DEA problem (A) for all years considered. Allowing for optimal reallocation of land use,
345 the maximum current-value profit is on average £ 195,488 for DEA problem (B). The increase
346 in maximum current-value profit is associated with an increase in the Shannon index for crop
347 diversity from on average 0.85 to 1.13 for all years considered. This pattern is consistent for the
348 whole period.

349 INSERT TABLE 2 AROUND HERE

350 Figure 1 illustrates the change in land use in percentage units that corresponds to the optimal
351 change in the Shannon index for crop diversity. It suggests that some land use allocated to
352 wheat, beans and potatoes should shift towards barley, peas, oats and sugar beet. This pattern
353 generally holds, although there are annual fluctuations possibly due to changing market and
354 weather conditions. Note that market conditions and restrictions on crop rotation may prevent
355 farmers from optimally allocating land use. For instance, since wheat is highly marketable,
356 farmers may choose to continue producing at a higher level than the level suggested by our
357 dynamic profit-maximisation model.

358 INSERT FIGURE 1 AROUND HERE

359 Table 3 shows the computed opportunity costs of crop diversification obtained by Eq. (9). In
360 what follows, we express the opportunity cost as the average cost (in constant 2007 £) of
361 increasing the Shannon index by 0.1 unit per hectare. The average opportunity cost is - £ 101
362 for the period, ranging from - £ 244 (in 2009) to £ 34 (in 2007), where only one year shows an
363 average positive opportunity cost. This means that farms are on average willing to pay for crop
364 diversification.

365 67% of the full sample have a negative opportunity cost for crop diversification. The majority
366 of the farms are thus willing to pay for an increase in the Shannon index for crop diversity. 19%
367 of the calculated opportunity costs are zero, and only 15% are positive. This proportion is
368 consistent for the whole time period.

369 INSERT TABLE 3 AROUND HERE

370 Table 4 presents the actual share and share under optimal reallocation of land use according to
371 DEA problem (B) that would have complied with the CAP's '2 or 3 crop rule'. Since all farms

372 in the sample cover more than 30 hectares, the most stringent rule would have been applied. All
373 farms should have produced at least three crops, where the main crop should not have covered
374 more than 75% of the arable land and the two main crops together not more than 95%. 57% of
375 the observations would have complied with the ‘2 or 3 crop rule’. However, if farms would
376 have optimally reallocated their land use, this share increases to 84%. This pattern is consistent
377 for the whole time period.

378 INSERT TABLE 4 AROUND HERE

379 *4.2. Robustness Checks*

380 We conduct three robustness checks. First, we investigate the results for the subsample of farms
381 that obtain current-value profits close to their optimal level. Our opportunity cost measure
382 assumes that farms would reallocate land use so as to maximise profit in the long run. Along
383 the lines of Wossink and Swinton (2007), we thus assume that farms are only interested in crop
384 diversification to the extent that it increases current-value profit. However, some farmers may
385 not operate under this behavioural assumption as they are motivated by social and lifestyle goals
386 (Howley, 2015). This robustness check thus focuses on the farms who are likely interested in
387 dynamic profit maximisation. Second, we check the results for the subsample excluding
388 outliers. Such a robustness check is useful as DEA is sensitive to outliers. Third, we investigate
389 the results using the FDH approach, which relaxes the convexity assumption of the technology
390 set. All tables for the robustness checks can be found in the Online Appendix.

391 *4.2.1. Non-Profit-Maximising Behaviour*

392 Table B1 shows the share of farms that have a dynamic profit efficiency of 80% or more for
393 DEA problems (A) and (B). We only take into account the farms that have a positive maximum
394 current-value profit for DEA problems (A) and (B)³. 36% of the observations have a dynamic
395 profit efficiency of 80% or more for DEA problem (A). The share ranges from 30% (in 2011)
396 to 52% (in 2007). 26% of the observations have a dynamic profit efficiency of 80% or more for
397 DEA problem (B). The share ranges from 16% (in 2009) to 41% (in 2007).

398 There are thus many observations with resource allocations deviating greatly from the long-run
399 profit-maximising point. This may indicate that the concerned farms are not long-term profit

³ Since total land is implemented as a fixed factor, the maximum current-value profit is negative for several observations, especially for bad years such as 2009.

400 maximisers⁴. Table B2 inspects the opportunity costs for the farms that have a dynamic profit
401 efficiency (*i.e.*, ratio of actual current-value profit to maximum current-value profit) of 80% or
402 more for DEA problems (A) and (B). As for the general results, the computed opportunity costs
403 are on average negative and are only positive on average for one year. Their average opportunity
404 cost is – £ 69 for the period, ranging from – £ 302 (in 2008) to £ 27 (in 2011).

405 On average 47% of the farms with a dynamic profit efficiency of 80% or more for DEA problem
406 (B) have a negative opportunity cost, while 17% have a positive cost. Only in the year 2011,
407 did the number of farms with a positive opportunity cost exceed the number of farms with a
408 negative opportunity cost. Observe that the dynamically profit efficient farms following DEA
409 problem (B) (36%) have by definition zero opportunity cost of crop diversification, as their land
410 allocation should not be changed.

411 Table B3 shows the actual share and share under optimal reallocation of land use according to
412 DEA problem (B) that would have complied with the CAP's '2 or 3 crop rule' for the farms
413 with a dynamic profit efficiency of 80% or more. 57% of these observations would have
414 complied with the '2 or 3 crop rule'. If farms would have optimally reallocated their land use,
415 this share increases to 75%. This pattern is consistent for the whole time period (except for the
416 year 2010, where the estimated share for DEA problem (B) is equal to the actual share).

417 4.2.2. *Outliers*

418 Following Oude Lansink and Silva (2004), we truncate the original sample by excluding
419 observations that are at least two standard deviations from the mean, to check the robustness to
420 outliers. Table C1 shows the opportunity costs of this truncated subsample. The resulting
421 opportunity costs are on average negative for each year. Their average opportunity cost is – £
422 28 for the period, ranging from – £ 91 (in 2013) to – £ 3 (in 2010). 43% of the farms from the
423 truncated subsample have a negative opportunity cost and 17% a positive cost.

424 Table C2 reveals that more farms from the truncated subsample would comply with the '2 or 3
425 crop rule' if they would have optimally reallocated their land use. Dynamic profit maximisation
426 allowing for reallocation of land use leads to an increase in compliance from 57% to 84%. This
427 pattern is consistent for the whole period.

428 4.2.3. *Non-Convexity*

⁴ Obtaining the shadow price by using the dual relationship of the value function to the distance function faces a similar issue, as this depends on an arbitrary projection to the technological frontier. This is particularly a problem for very inefficient farms where the shadow price is sensitive to the choice of the directional vector or orientation.

429 Table D1 shows the opportunity costs of crop diversification using the FDH model. The
430 resulting opportunity costs are on average £ 35 considering the whole period, with a minimum
431 of – £ 21 (in 2008) and a maximum of £ 77 (in 2010). 31% (15%) of the farms have a negative
432 (positive) opportunity cost. This pattern holds for the whole period. Note that the FDH model
433 allows for non-convexity of the technology set, but results in reduced detection of non-
434 optimising farms. Therefore, the share of farms with a zero opportunity cost is high (55%).
435 Table D2 shows the actual share and share under optimal reallocation of land use according to
436 problem (B) adjusted for non-convexity that would have complied with the CAP’s ‘2 or 3 crop
437 rule’. Dynamic profit maximisation allowing for reallocation of land use leads to an increase in
438 compliance from 57% to 67%. This pattern is consistent for the whole period. Again, these
439 gains are somewhat more modest due to a lower detection of non-optimising farms inherent to
440 the FDH model.

441 *4.3. Comparison to Usual Shadow-Pricing Approach*

442 The prevailing negative opportunity costs contrast with the imposed non-negative shadow
443 prices of the usual approach of modelling environmental goods as conventional outputs in a
444 distance function framework. Sipiläinen and Huhtala (2013) also computed the opportunity cost
445 of the Shannon index for crop diversity using the distance function’s dual relationship to the
446 value function. They found an average opportunity cost between £ 12 and £ 45 (in constant
447 2007 terms) per 0.1 ha for a sample of Finnish cereal farms. We apply their approach for
448 comparison (see Appendix E) and show the results in table 5. We run their model for each farm
449 in the sample in each year to ensure comparability with our proposed approach. The estimated
450 shadow price is £ 79 for the period, ranging from £ 22 (in 2008) to £ 212 (in 2013). As expected,
451 these results are non-negative, which contradict the results of our introduced opportunity cost
452 measure.

453 INSERT TABLE 5 AROUND HERE

454

455 **5. Discussion**

456 Our main finding is that dynamic profit-maximisation allowing for optimal land reallocation is
457 generally associated with an increase in the Shannon index for crop diversity. The opportunity
458 cost of crop diversification is mostly negative and most farms would have complied with the ‘2
459 or 3 crop rule’ recently imposed by the CAP if they had optimally reallocated their land use.
460 These results are robust to excluding observations far from the dynamic profit-maximising
461 point, excluding outliers, and allowing non-convexity of the technology set. Negative

462 opportunity costs could not have been obtained by exploiting the distance function's dual
463 relationship to the value function as commonly done in the literature. Our results are in line
464 with the conceptual and empirical work of respectively Wossink and Swinton (2007) and Sauer
465 and Wossink (2013), who argue that many farms would be willing to pay to increase the
466 provision of environmental goods as its relationship with conventional production is not purely
467 competitive. This coincides with the ecological perspective that environmental measures may
468 be needed for long-term economic benefits.

469 Since nonparametric models are in essence deterministic, we have implicitly assumed that
470 farms can perfectly foresee the outcomes of their production decisions. However, there is in
471 reality considerable uncertainty in agricultural production due to unforeseen weather
472 conditions. As a result, our model may compare farms that have different output realisations
473 due to different 'States of Nature' (Quiggin and Chambers, 2006). We partially control for this
474 issue by running the DEA models per year. For instance, since 2009 clearly marks a year with
475 a bad State of Nature, the reference technology only consists of observations for the year 2009.
476 One could consider controlling for this issue even more by also running the DEA models per
477 government office region. However, subdividing our sample into smaller subsamples leads to
478 dimensionality problems given the large number of inputs, outputs and net investments in
479 dynamic factors compared to the relatively low number of observations. Moreover, all farms
480 considered are located in the East of England, which is a fairly homogeneous region with similar
481 weather conditions. This ensures that the bias due to different States of Nature at the time of
482 production is small. Note that our findings are persistent for each of the seven years considered,
483 hold for the subsample of farms with a dynamic profit efficiency of 80% or more, is robust to
484 excluding extreme observations, and hold for a non-convex production technology.

485 In the light of the 'Green Direct Payment' measure introduced recently by the CAP, we may
486 reflect on whether the relative robustness of our results translates into predictive power. On the
487 one hand, the predicted potential is possibly underestimated. We have aggregated spring and
488 winter crops as these belong to the same species. However, according to the '2 or 3 crop rule',
489 spring and winter crops can be counted as separate crops. Also fallow land can be counted
490 separately according to this rule. Although we take this into account in our calculations, these
491 are assumed to be non-reallocatable inputs that jointly contribute to the production of
492 marketable outputs. In addition, it is plausible that farmers use crop diversification as a risk-
493 reducing mechanism, even if it would lead to lower rather than higher expected profits (Di Falco
494 and Chavas, 2008; Di Falco and Chavas, 2009). On the other hand, there are also several reasons

495 to believe that the predicted potential is overestimated. There is plenty of evidence of persistent
496 inefficient behaviour due to inherent non-economic objectives (Howley, 2015) or persistent
497 technical inefficiency (Emvalomatis, Stefanou et al., 2011). Such dynamic profit inefficiency
498 is also present in the current study. Moreover, although dynamic profit maximisation would
499 lead to a shift to more profitable products such as barley, this remains constrained by market
500 conditions and limitations on crop rotation. In summary, although our findings suggest no
501 general justification of subsidisation of crop diversification, we remain cautious about the
502 predictive power of our model.

503 **6. Conclusions**

504 Distance functions are increasingly being augmented with environmental goods treated as
505 outputs to assess the trade-off between environmental goods and outputs. A common approach
506 to evaluate the opportunity cost of providing an environmental good is the exploitation of the
507 distance function's dual relationship to the value function. However, this approach may rely on
508 problematic assumptions about the environmental goods' axiomatic properties. In particular, it
509 is assumed that an environmental good can be treated as a conventional, strongly disposable
510 output and that its shadow price is as a result always non-negative. Moreover, the convexity
511 assumption of the augmented environmental technology set is necessary to ensure that the
512 output distance function's dual relationship to the revenue function holds.

513 Focusing on crop diversification, this paper develops an opportunity cost measure that
514 overcomes these drawbacks for a sample of English cereal farms covering the years 2007-2013.
515 Using a nonparametric model, we assess the extent to which reallocation of land use can
516 increase current-value profit. As this increase is linked to a change of the Shannon index for
517 crop diversity, this allows us to express the opportunity cost of crop diversification in terms of
518 foregone current-value profit. Our proposed measure relies solely on standard axiomatic
519 properties of conventional inputs and outputs, does not critically depend on convexity of the
520 technology set, and is consistent with the behavioural assumption of dynamic profit-
521 maximisation. Our results are robust to excluding observations far from the dynamic profit-
522 maximising point, excluding outliers, and relaxing the convexity assumption of the technology
523 set.

524 The results show that the opportunity cost of crop diversification is mostly negative. This is an
525 interesting outcome, as distance functions augmented with environmental goods treated as
526 outputs implicitly assume that shadow prices of environmental goods are always non-negative.
527 The results also indicate that optimal reallocation of land use, which would have maximised

528 dynamic profit, would have led to increased compliance with the CAP's recently introduced '2
529 or 3 crop rule'. These results may be interpreted that crop diversification does not generally
530 justify subsidies, suggesting a reconsideration of the financial mechanism of the CAP's Green
531 Direct Payment measure. However, we remain cautious about the general policy implications
532 of the results, for we have focused on a sample of specialised farms in a particular region (East
533 of England). Additionally, we have observed high dynamic profit inefficiency, which is likely
534 to persist after the introduction of the '2 or 3 crop rule'. Finally, market conditions and
535 limitations on crop rotation may limit shifts to the dynamic profit-maximising land allocation.

536 We have several suggestions for future research. First, there is a demand from policy makers to
537 develop a holistic sustainability measure which incorporates environmental goods and bads in
538 a rigorous way. Understanding the trade-offs among inputs, outputs, and environmental goods
539 and bads is essential to this end. Our measure has explicitly separated the environmental good
540 from the production technology. There could be other ways to realistically model environmental
541 goods and bads within the production technology. Murty, Russell et al. (2012) develop distance
542 functions that specifically model the pollution-generating inputs. It may be worthwhile to also
543 model the inputs that generate environmental goods. Second, our measure can be augmented
544 by taking into account spatial heterogeneity, which occurs due to different environmental
545 circumstances and market conditions (Polasky, Nelson et al., 2008; Nelson, Mendoza et al.,
546 2009). Third, our measure can be extended by accounting for risk along the lines of Chavas and
547 Di Falco (2012), since crop diversification is an important mechanism of risk reduction,
548 potentially at the expense of expected profits.

549 **On-Line Appendix A**

550 Following Kuosmanen, Kortelainen et al. (2010), we solve the following linear problem to find
 551 values for $W_K(\cdot)$ for each farm $j \in \mathbb{R}_+^J$:

552 (C)
$$\min_{\{p,w,v,W_K,\rho\}} \rho$$

553 *s.t.*

554 (C.1)
$$\rho \geq (p'y - w'x - v'L + W_K'(I - \delta K)) - (p'y_i - w'x_i - v'L_i + W_K'(I_i -$$

 555
$$\delta_i K_i)), i = 1, \dots, J$$

556 (C.2)
$$p'g_y + w'g_x + v'g_L + W_K'g_I = 1, (g_y, g_x, g_I, g_L) = \left(\frac{1}{p}, 0, 0, 0\right)$$

557 (C.3)
$$p'g_y + w'g_x + v'g_L + W_K'g_I = 1, (g_y, g_x, g_I, g_L) = \left(0, \frac{1}{w}, 0, 0\right)$$

558 (C.4)
$$p \geq 0$$

559 (C.5)
$$w \geq 0$$

560 (C.6)
$$v \geq 0$$

561 (C.7)
$$W_K \geq 0$$

562 where $y \in \mathbb{R}_+^1$ is the aggregated output vector, $x \in \mathbb{R}_+^1$ is the aggregated variable input vector,
 563 $K_t \in \mathbb{R}_+^F$ is the initial capital stock vector, $I \in \mathbb{R}_+^F$ is the investment vector, $L \in \mathbb{R}_+^2$ is the vector
 564 of fixed factors consisting of total agricultural land area and family labor, $p \in \mathbb{R}_+^1$ is the vector
 565 of aggregated output prices, $w \in \mathbb{R}_+^1$ is the vector of aggregated input prices, $v \in \mathbb{R}_+^2$ is the
 566 vector of fixed factor prices, $c \in \mathbb{R}_+^F$ is the vector of capital prices, $W_K \in \mathbb{R}_+^F$ is the vector of
 567 shadow values of capital, δ is a diagonal $F \times F$ matrix of depreciation rates $\delta_f > 0, f, \dots, F$
 568 (g_y, g_x, g_I, g_L) is the directional vector in terms of outputs, inputs, investment and fixed factors.
 569 Outputs and inputs are aggregated by Törnqvist price indexes to reduce dimensionality. This
 570 means that quality differences are assumed to be revealed by the implicit quantity (Cox and
 571 Wohlgenant, 1986). This model is run per year. It also solves for the prices $v \in \mathbb{R}_+^2$ of the
 572 vector of fixed factors (total land and family labour). By setting $(g_y, g_x, g_L, g_I) = \left(\frac{1}{p}, 0, 0, 0\right)$
 573 and $(g_y, g_x, g_L, g_I) = \left(0, \frac{1}{w}, 0, 0\right)$ in respectively C.2 and C.3, we ensure that L is treated as a
 574 vector of fixed factors and the known information on output and input prices is incorporated in
 575 the model. The farm-specific values for W_K are plugged into DEA problems (A) and (B).

576 **On-Line Appendix B**

577 **Table B1. Share of farms with a dynamic profit efficiency of 80% or more for DEA problems (A) and (B),**
 578 **2007-2013**

| Year | Share for DEA problem (A) | Share for DEA problem (B) |
|--------|---------------------------|---------------------------|
| 2007 | 52% | 41% |
| 2008 | 43% | 39% |
| 2009 | 30% | 16% |
| 2010 | 32% | 18% |
| 2011 | 30% | 27% |
| 2012 | 32% | 20% |
| 2013 | 34% | 23% |
| Period | 36% | 26% |

579

580 **Table B2. Opportunity costs of the Shannon index for crop diversification per 0.1 ha for farms with a**
 581 **dynamic profit efficiency of 80% or more for DEA problem (B) using the proposed method, 2007-2013**

| Year | Number of farms | Average (in constant 2007 £) | Std. Dev. (in constant 2007 £) | Share | | |
|--------|-----------------|------------------------------|--------------------------------|----------|-----|----------|
| | | | | Negative | 0 | Positive |
| 2007 | 18 | -17 | 169 | 39% | 50% | 11% |
| 2008 | 17 | -302 | 1342 | 59% | 29% | 12% |
| 2009 | 7 | -1 | 3 | 29% | 71% | 0% |
| 2010 | 8 | -14 | 42 | 38% | 38% | 25% |
| 2011 | 12 | 27 | 47 | 33% | 25% | 42% |
| 2012 | 9 | -12 | 46 | 44% | 22% | 33% |
| 2013 | 10 | -22 | 24 | 80% | 20% | 0% |
| Period | 81 | -69 | 618 | 47% | 36% | 17% |

582

583

584 **Table B3. Actual share and share under optimal reallocation of land use according to DEA problem (B)**
 585 **that would have complied with the CAP's '2 or 3 crop rule' for farms with a dynamic profit efficiency of**
 586 **80% or more, 2007-2013**

| Year | Actual share | Estimated share for DEA problem (B) | Gains from optimal reallocation in percentage units |
|--------|--------------|-------------------------------------|---|
| 2007 | 61% | 72% | +11% |
| 2008 | 47% | 71% | +24% |
| 2009 | 57% | 86% | +19% |
| 2010 | 63% | 63% | +0% |
| 2011 | 58% | 83% | +25% |
| 2012 | 56% | 78% | +22% |
| 2013 | 60% | 80% | +20% |
| Period | 57% | 75% | +17% |

587

588

589 **On-Line Appendix C**

590 **Table C1. Opportunity costs of the Shannon index for crop diversification per 0.1 ha for subsample**
 591 **excluding outliers, 2007-2013**

| Year | Number of farms | Average (in constant 2007 £) | Std. Dev. (in constant 2007 £) | Share | | |
|--------|-----------------|------------------------------|--------------------------------|----------|-----|----------|
| | | | | Negative | 0 | Positive |
| 2007 | 42 | -9 | 105 | 55% | 26% | 19% |
| 2008 | 43 | -25 | 144 | 72% | 19% | 9% |
| 2009 | 43 | -15 | 210 | 77% | 19% | 5% |
| 2010 | 41 | -3 | 75 | 59% | 24% | 17% |
| 2011 | 43 | -42 | 163 | 58% | 19% | 23% |
| 2012 | 43 | -28 | 240 | 65% | 16% | 19% |
| 2013 | 43 | -91 | 174 | 81% | 12% | 7% |
| Period | 298 | -28 | 169 | 67% | 19% | 14% |

592

593 **Table C2. Actual share and share under optimal reallocation of land use according to DEA problem (B)**
 594 **that would have complied with the CAP's '2 or 3 crop rule' for subsample excluding outliers, 2007-2013**

| Year | Actual share | Estimated share for DEA problem (B) | Gains in share from optimal reallocation in percentage units |
|--------|--------------|-------------------------------------|--|
| 2007 | 50% | 76% | +26% |
| 2008 | 51% | 88% | +37% |
| 2009 | 60% | 98% | +37% |
| 2010 | 56% | 80% | +24% |
| 2011 | 53% | 72% | +29% |
| 2012 | 58% | 84% | +26% |
| 2013 | 67% | 91% | +23% |
| Period | 57% | 84% | +28% |

595

596

597 **On-Line Appendix D**

598 **Table D1. Opportunity costs of the Shannon index for crop diversification per 0.1 ha using the proposed**
 599 **method adjusted for non-convexity, 2007-2013**

| Year | Number of farms | Average (in constant 2007 £) | Std. Dev. (in constant 2007 £) | Share | | |
|--------|-----------------|------------------------------|--------------------------------|----------|-----|----------|
| | | | | Negative | 0 | Positive |
| 2007 | 44 | 13 | 164 | 23% | 55% | 23% |
| 2008 | 44 | -35 | 286 | 27% | 57% | 16% |
| 2009 | 44 | -21 | 97 | 39% | 39% | 23% |
| 2010 | 44 | 77 | 639 | 39% | 55% | 7% |
| 2011 | 44 | 16 | 184 | 34% | 57% | 9% |
| 2012 | 44 | 23 | 202 | 25% | 64% | 11% |
| 2013 | 44 | 70 | 532 | 27% | 57% | 16% |
| Period | 308 | 21 | 354 | 31% | 55% | 15% |

600

601 **Table D2. Actual share and share under optimal reallocation of land use according to problem (B) adjusted**
 602 **for non-convexity that would have complied with the CAP's '2 or 3 crop rule'**

| Year | Actual share | Estimated share for problem (B) adjusted for non-convexity | Gains from optimal reallocation in percentage units |
|--------|--------------|--|---|
| 2007 | 52% | 57% | +5% |
| 2008 | 52% | 64% | +11% |
| 2009 | 61% | 75% | +14% |
| 2010 | 57% | 73% | +16% |
| 2011 | 55% | 66% | +11% |
| 2012 | 57% | 66% | +9% |
| 2013 | 68% | 70% | +2% |
| Period | 57% | 67% | +10% |

603

604

605 **On-Line Appendix E**

606 We exploit the directional distance function's dual relationship to the profit function by solving
 607 a minimax problem similar to linear program (C) in line with Kuosmanen, Kortelainen et al.
 608 (2010). We solve the following linear problem to find shadow price u for each farm $j \in \mathbb{R}_+^J$:

609 (D)
$$\min_{\{p,w,v,u,\theta\}} \theta$$

610 *s.t.*

611 (D.1)
$$\theta \geq (p'y - w'x - v'L + u'S(\cdot)^{(1)}) - (p'y_i - w'x_i - v'L_i + u'S(\cdot)^{(1)}), i =$$

 612
$$1, \dots, J$$

613 (D.2)
$$p'g_y + w'g_x + v'g_L + u'g_S = 1, (g_y, g_x, g_L, g_S) = \left(\frac{1}{p}, 0, 0, 0\right)$$

614 (D.3)
$$p'g_y + w'g_x + v'g_L + u'g_S = 1, (g_y, g_x, g_L, g_S) = \left(0, \frac{1}{w}, 0, 0\right)$$

615 (D.4)
$$p \geq 0$$

616 (D.5)
$$w \geq 0$$

617 (D.6)
$$v \geq 0$$

618 (D.7)
$$u \geq 0$$

619 where $y \in \mathbb{R}_+^1$ is the aggregated output vector, $x \in \mathbb{R}_+^1$ is the aggregated variable input vector,
 620 $L \in \mathbb{R}_+^2$ is the vector of fixed factors consisting of total agricultural land area and family labour,
 621 $S(\cdot)^{(1)}$ is the Shannon index for crop diversity computed by Eq. (9), $p \in \mathbb{R}_+^1$ is the vector of
 622 aggregated output prices, $w \in \mathbb{R}_+^1$ is the vector of aggregated input prices, $v \in \mathbb{R}_+^2$ is the vector
 623 of fixed factor prices, $u \in \mathbb{R}_+^1$ is the vector of shadow values of capital, δ is a diagonal $F \times F$
 624 matrix of depreciation rates $\delta_f > 0, f, \dots, F$. (g_y, g_x, g_L, g_S) is the directional vector in terms
 625 of outputs, inputs, fixed factors and the Shannon index for crop diversity. Outputs and inputs
 626 are aggregated by Törnqvist price indexes to reduce dimensionality. This means that quality
 627 differences are assumed to be revealed by the implicit quantity (Cox and Wohlgenant, 1986).
 628 This model is run per year. It also solves for the prices $v \in \mathbb{R}_+^2$ of the vector of fixed factors
 629 (total land and family labor). By setting $(g_y, g_x, g_L, g_S) = \left(\frac{1}{p}, 0, 0, 0\right)$ and $(g_y, g_x, g_L, g_S) =$
 630 $\left(0, \frac{1}{w}, 0, 0\right)$ in respectively C.2 and C.3, we ensure that L is treated as a vector of fixed factors
 631 and the known information on output and input prices is incorporated in the model.

632

633 **References**

- 634 Aguilar, J., G.G. Gramig, J.R. Hendrickson, D.W. Archer, F. Forcella and M.A. Liebig "Crop
635 Species Diversity Changes in the United States: 1978–2012." *PLoS ONE*, Vol. **10**,
636 (2015) pp. e0136580.
- 637 Ang, F. and P.J. Kerstens "To Mix or Specialise? A Coordination Productivity Indicator for
638 English and Welsh farms." *Journal of Agricultural Economics*, Vol. **67**, (2016) pp.
639 779-798.
- 640 Ang, F. and P.J. Kerstens "Decomposing the Luenberger-Hicks-Moorsteen Total Factor
641 Productivity indicator: An application to US agriculture." *European Journal of*
642 *Operational Research*, Vol. **260**, (2017) pp. 359-375.
- 643 Ang, F. and A. Oude Lansink *Decomposing Dynamic Profit Inefficiency of Belgian Dairy*
644 *Farms*, 2016).
- 645 Ang, F. and A. Oude Lansink "Decomposing dynamic profit inefficiency of Belgian dairy
646 farms." *European Review of Agricultural Economics*, (2017) pp. 1-19.
- 647 Areal, F.J., R. Tiffin and K.G. Balcombe "Provision of environmental output within a multi-
648 output distance function approach." *Ecological Economics*, Vol. **78**, (2012) pp. 47-54.
- 649 Bellenger, M.J. and A.T. Herlihy "An economic approach to environmental indices."
650 *Ecological Economics*, Vol. **68**, (2009) pp. 2216-2223.
- 651 Bellenger, M.J. and A.T. Herlihy "Performance-based environmental index weights: Are all
652 metrics created equal?" *Ecological Economics*, Vol. **69**, (2010) pp. 1043-1050.
- 653 Bostian, M.B. and A.T. Herlihy "Valuing tradeoffs between agricultural production and
654 wetland condition in the U.S. Mid-Atlantic region." *Ecological Economics*, Vol. **105**,
655 (2014) pp. 284-291.

656 Briec, W., K. Kerstens and P.V. Eeckaut "Non-convex Technologies and Cost Functions:
657 Definitions, Duality and Nonparametric Tests of Convexity." *Journal of Economics*,
658 Vol. **81**, (2004) pp. 155-192.

659 Chambers, R.G., T. Serra and A. Oude Lansink "On the pricing of undesirable state-
660 contingent outputs." *European Review of Agricultural Economics*, Vol. **41**, (2014) pp.
661 485-509.

662 Chavas, J.-P. and S. Di Falco "On the Role of Risk Versus Economies of Scope in Farm
663 Diversification With an Application to Ethiopian Farms." *Journal of Agricultural*
664 *Economics*, Vol. **63**, (2012) pp. 25-55.

665 Cherchye, L., B. De Rock, B. Dierynck, F. Roodhooft and J. Sabbe "Opening the "Black Box"
666 of Efficiency Measurement: Input Allocation in Multioutput Settings." *Operations*
667 *Research*, Vol. **61**, (2013) pp. 1148-1165.

668 Cherchye, L., B. De Rock and V. Hennebel "Coordination efficiency in multi-output settings:
669 a DEA approach." *Annals of Operations Research*, (2015) pp. 1-29.

670 Cherchye, L., B. De Rock and V. Hennebel "Coordination efficiency in multi-output settings:
671 a DEA approach." *Annals of Operations Research*, Vol. **250**, (2017) pp. 205-233.

672 Coelli, T., L. Lauwers and G. Van Huylenbroeck "Environmental efficiency measurement and
673 the materials balance condition." *Journal of Productivity Analysis*, Vol. **28**, (2007) pp.
674 3-12.

675 Cox, T.L. and M.K. Wohlgenant "Prices and Quality Effects in Cross-Sectional Demand
676 Analysis." *American Journal of Agricultural Economics*, Vol. **68**, (1986) pp. 908-919.

677 Dakpo, K.H., P. Jeanneaux and L. Latruffe "Greenhouse gas emissions and efficiency in
678 French sheep meat farming: A non-parametric framework of pollution-adjusted
679 technologies." *European Review of Agricultural Economics*, Vol. **44**, (2017) pp. 33-
680 65.

681 Di Falco, S. and J.-P. Chavas "Rainfall shocks, resilience, and the effects of crop biodiversity
682 on agroecosystem productivity." *Land Economics*, Vol. **84**, (2008) pp. 83-96.

683 Di Falco, S. and J.-P. Chavas "On Crop Biodiversity, Risk Exposure, and Food Security in the
684 Highlands of Ethiopia." *American Journal of Agricultural Economics*, Vol. **91**, (2009)
685 pp. 599-611.

686 Emvalomatis, G., S.E. Stefanou and A. Oude Lansink "A Reduced-Form Model for Dynamic
687 Efficiency Measurement: Application to Dairy Farms in Germany and The
688 Netherlands." *American Journal of Agricultural Economics*, Vol. **93**, (2011) pp. 161-
689 174.

690 European Parliament, C.o.t.E.U. "Regulation (EU) No 1307/2013 of the European Parliament
691 and of the Council of 17 December 2013 establishing rules for direct payments to
692 farmers under support schemes within the framework of the common agricultural
693 policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation
694 (EC) No 73/2009", *Official Journal of the European Union*, 2013).

695 EUROSTAT, 2015).

696 Färe, R., R. Grabowski, S. Grosskopf and S. Kraft "Efficiency of a fixed but allocatable input:
697 A non-parametric approach." *Economics Letters*, Vol. **56**, (1997) pp. 187-193.

698 Färe, R. and S. Grosskopf *New Directions: Efficiency and Productivity*, Springer US, 2005).

699 Färe, R., S. Grosskopf and W.L. Weber "Shadow prices of Missouri public conservation
700 land." *Public Finance Review*, Vol. **29**, (2001) pp. 444-460.

701 Harvey, D.R. "Agri-environmental Relationships and Multi-functionality: Further
702 Considerations." *World Economy*, Vol. **26**, (2003) pp. 705-725.

703 Henry, M., P. Tittonell, R.J. Manlay, M. Bernoux, A. Albrecht and B. Vanlauwe
704 "Biodiversity, carbon stocks and sequestration potential in aboveground biomass in

705 smallholder farming systems of western Kenya." *Agriculture, Ecosystems &*
706 *Environment*, Vol. **129**, (2009) pp. 238-252.

707 Hodge, I.D. "Agri-environmental relationships and the choice of policy mechanism." *The*
708 *World Economy*, Vol. **23**, (2000) pp. 257-273.

709 Hodge, I.D. *To What Extent are Environmental Externalities a Joint Product of Agriculture?*,
710 OECD Publishing, 2008).

711 Howley, P. "The Happy Farmer: The Effect of Nonpecuniary Benefits on Behavior."
712 *American Journal of Agricultural Economics*, Vol. **97**, (2015) pp. 1072-1086.

713 Kuosmanen, T. "Duality Theory of Non-convex Technologies." *Journal of Productivity*
714 *Analysis*, Vol. **20**, (2003) pp. 273-304.

715 Kuosmanen, T., M. Kortelainen, T. Sipiläinen and L. Cherchye "Firm and industry level profit
716 efficiency analysis using absolute and uniform shadow prices." *European Journal of*
717 *Operational Research*, Vol. **202**, (2010) pp. 584-594.

718 Macpherson, A.J., P.P. Principe and E.R. Smith "A directional distance function approach to
719 regional environmental–economic assessments." *Ecological Economics*, Vol. **69**,
720 (2010) pp. 1918-1925.

721 Murty, S., R.R. Russell and S.B. Levkoff "On modeling pollution-generating technologies."
722 *Journal of Environmental Economics and Management*, Vol. **64**, (2012) pp. 117-135.

723 Nelson, E., G. Mendoza, J. Regetz, S. Polasky, H. Tallis, D. Cameron, K.M.A. Chan, G.C.
724 Daily, J. Goldstein, P.M. Kareiva, E. Lonsdorf, R. Naidoo, T.H. Ricketts and M. Shaw
725 "Modeling multiple ecosystem services, biodiversity conservation, commodity
726 production, and tradeoffs at landscape scales." *Frontiers in Ecology and the*
727 *Environment*, Vol. **7**, (2009) pp. 4-11.

728 Oude Lansink, A. and E. Silva "CO2 and energy efficiency of different heating technologies
729 in the Dutch glasshouse industry." *Environmental & Resource Economics*, Vol. **24**,
730 (2003) pp. 395-407.

731 Oude Lansink, A. and E. Silva "Non-parametric production analysis of pesticides use in the
732 Netherlands." *Journal of Productivity Analysis*, Vol. **21**, (2004) pp. 49-65.

733 Pimentel, D., P. Hepperly, J. Hanson, D. Douds and R. Seidel "Environmental, energetic, and
734 economic comparisons of organic and conventional farming systems." *Bioscience*,
735 Vol. **55**, (2005) pp. 573-582.

736 Piot-Lepetit, I. and M. Le Moing "Productivity and environmental regulation: the effect of the
737 nitrates directive in the French pig sector." *Environmental & Resource Economics*,
738 Vol. **38**, (2007) pp. 433-446.

739 Piot-Lepetit, I. and D. Vermersch "Pricing organic nitrogen under the weak disposability
740 assumption: An application to the French pig sector." *Journal of Agricultural*
741 *Economics*, Vol. **49**, (1998) pp. 85-99.

742 Polasky, S., E. Nelson, J. Camm, B. Csuti, P. Fackler, E. Lonsdorf, C. Montgomery, D.
743 White, J. Arthur, B. Garber-Yonts, R. Haight, J. Kagan, A. Starfield and C. Tobalske
744 "Where to put things? Spatial land management to sustain biodiversity and economic
745 returns." *Biological Conservation*, Vol. **141**, (2008) pp. 1505-1524.

746 Pope, B. and A. Johnson "Returns to scope: a metric for production synergies demonstrated
747 for hospital production." *Journal of Productivity Analysis*, Vol. **40**, (2013) pp. 239-
748 250.

749 Quiggin, J. and R.G. Chambers "The state-contingent approach to production under
750 uncertainty*." *The Australian Journal of Agricultural and Resource Economics*, Vol.
751 **50**, (2006) pp. 153-169.

752 Reinhard, S., C.A.K. Lovell and G. Thijssen "Econometric estimation of technical and
753 environmental efficiency: An application to Dutch dairy farms." *American Journal of*
754 *Agricultural Economics*, Vol. **81**, (1999) pp. 44-60.

755 Reinhard, S., C.A.K. Lovell and G.J. Thijssen "Environmental efficiency with multiple
756 environmentally detrimental variables; estimated with SFA and DEA." *European*
757 *Journal of Operational Research*, Vol. **121**, (2000) pp. 287-303.

758 Ruijs, A., M. Kortelainen, A. Wossink, C.J.E. Schulp and R. Alkemade "Opportunity Cost
759 Estimation of Ecosystem Services." *Environmental and Resource Economics*, Vol. **66**,
760 (2017) pp. 717-747.

761 Ruijs, A., A. Wossink, M. Kortelainen, R. Alkemade and C.J.E. Schulp "Trade-off analysis of
762 ecosystem services in Eastern Europe." *Ecosystem Services*, Vol. **4**, (2013) pp. 82-94.

763 Sauer, J. and A. Wossink "Marketed outputs and non-marketed ecosystem services: the
764 evaluation of marginal costs." *European Review of Agricultural Economics*, Vol. **40**,
765 (2013) pp. 573-603.

766 Serra, T., R.G. Chambers and A. Oude Lansink "Measuring technical and environmental
767 efficiency in a state-contingent technology." *European Journal of Operational*
768 *Research*, Vol. **236**, (2014) pp. 706-717.

769 Silva, E., A. Oude Lansink and S.E. Stefanou "The adjustment-cost model of the firm: Duality
770 and productive efficiency." *International Journal of Production Economics*, Vol. **168**,
771 (2015) pp. 245-256.

772 Silva, E. and S.E. Stefanou "Nonparametric dynamic production analysis and the theory of
773 cost." *Journal of Productivity Analysis*, Vol. **19**, (2003) pp. 5-32.

774 Sipiläinen, T. and A. Huhtala "Opportunity costs of providing crop diversity in organic and
775 conventional farming: would targeted environmental policies make economic sense?"
776 *European Review of Agricultural Economics*, Vol. **40**, (2013) pp. 441-462.

777 Varian, H.R. "The nonparametric approach to production analysis." *Econometrica*, Vol. **52**,
778 (1984) pp. 579-597.

779 Vatn, A. "Multifunctional agriculture: some consequences for international trade regimes."
780 *European Review of Agricultural Economics*, Vol. **29**, (2002) pp. 309-327.

781 Weitzman, M.L. "Economic Profitability Versus Ecological Entropy." *The Quarterly Journal*
782 *of Economics*, Vol. **115**, (2000) pp. 237-263.

783 Westbury, D.B., J.R. Park, A.L. Mauchline, R.T. Crane and S.R. Mortimer "Assessing the
784 environmental performance of English arable and livestock holdings using data from
785 the Farm Accountancy Data Network (FADN)." *Journal of Environmental*
786 *Management*, Vol. **92**, (2011) pp. 902-909.

787 Wossink, A. and S.M. Swinton "Jointness in production and farmers' willingness to supply
788 non-marketed ecosystem services." *Ecological Economics*, Vol. **64**, (2007) pp. 297-
789 304.

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793 **Table 1. Descriptive statistics of the dataset (308 observations for 44 cereal farms), 2007-2013**

| Variables | Unit | Mean | Std. Dev. |
|---------------------------------------|----------------------|---------|-----------|
| Outputs | | | |
| Wheat | Constant 2007 £ | 173,175 | 242,325 |
| Barley | Constant 2007 £ | 7,815 | 16,023 |
| Oats | Constant 2007 £ | 3,583 | 9,818 |
| Beans | Constant 2007 £ | 4,242 | 14,516 |
| Peas | Constant 2007 £ | 8,184 | 31,342 |
| Potatoes | Constant 2007 £ | 51,797 | 75,696 |
| Sugar beet | Constant 2007 £ | 10,462 | 21,210 |
| Other outputs | Constant 2007 £ | 3,630 | 18,483 |
| Output-specific land | | | |
| Wheat | Hectares | 154 | 199 |
| Barley | Hectares | 10 | 19 |
| Oats | Hectares | 5 | 13 |
| Beans | Hectares | 6 | 14 |
| Peas | Hectares | 8 | 30 |
| Potatoes | Hectares | 51 | 65 |
| Sugar beet | Hectares | 6 | 12 |
| Other outputs | Hectares | 3 | 12 |
| Variable inputs | | | |
| Seed and planting stock | Constant 2007 £ | 28,186 | 41,084 |
| Fertilizer | Constant 2007 £ | 72,226 | 79,435 |
| Crop protection | Constant 2007 £ | 73,105 | 87,139 |
| Electricity | Constant 2007 £ | 2,995 | 6,091 |
| Heating fuel | Constant 2007 £ | 1,140 | 2,396 |
| External labor | Annual working hours | 2,829 | 3,927 |
| Management | Annual working hours | 16 | 114 |
| Other variable inputs | Constant 2007 £ | 9,714 | 14,144 |
| Investments | | | |
| Buildings | Constant 2007 £ | 6,566 | 23,596 |
| Machinery | Constant 2007 £ | 54,093 | 88,128 |
| Historical depreciation | | | |
| Buildings | Constant 2007 £ | 6,622 | 10,782 |
| Machinery | Constant 2007 £ | 31,078 | 38,539 |
| Fixed non-reallocatable inputs | | | |
| Grassland and other herbaceous forage | Hectares | 15 | 34 |
| Fallow land | Hectares | 2 | 7 |
| Family labour | Annual working hours | 1,865 | 822 |

794 **Table 2. Actual and maximum current-value profit and corresponding Shannon indexes for crop diversity**
 795 **for DEA problems (A) and (B), 2007-2013**

| Year | Actual current-value profit (in constant 2007 £) | Actual Shannon index for crop diversity | Maximum current-value profit for DEA problem (A) (in constant 2007 £) | Maximum current-value profit for DEA problem (B) (in constant 2007 £) | Shannon index for crop diversity for DEA problem (B) |
|--------|--|---|---|---|--|
| 2007 | 154,483 (314,419) | 0.87 (0.34) | 170,212 (310,268) | 195,978 (324,841) | 1.10 (0.37) |
| 2008 | 120,307 (173,665) | 0.81 (0.35) | 140,512 (168,810) | 175,024 (180,673) | 1.15 (0.33) |
| 2009 | - 38,429 (126,077) | 0.88 (0.34) | 5,724 (100,200) | 51,696 (105,261) | 1.29 (0.25) |
| 2010 | 122,038 (220,333) | 0.85 (0.41) | 144,279 (217,925) | 178,307 (229,371) | 1.16 (0.40) |
| 2011 | 176,152 (272,026) | 0.82 (0.34) | 225,998 (271,740) | 278,024 (294,843) | 0.96 (0.26) |
| 2012 | 210,096 (428,709) | 0.82 (0.33) | 270,091 (421,990) | 304,165 (425,447) | 1.06 (0.34) |
| 2013 | 122,651 (206,530) | 0.89 (0.38) | 145,034 (200,918) | 185,223 (214,574) | 1.19 (0.31) |
| Period | 123,900 (273,035) | 0.85 (0.35) | 157,407 (269,026) | 195,488 (279,285) | 1.13 (0.34) |

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798 **Table 3. Opportunity costs of the Shannon index for crop diversification per 0.1 ha using the proposed**
 799 **method, 2007-2013**

| Year | Number of farms | Average (in constant 2007 £) | Std. Dev. (in constant 2007 £) | Share | | |
|--------|-----------------|------------------------------|--------------------------------|----------|-----|----------|
| | | | | Negative | 0 | Positive |
| 2007 | 44 | 34 | 290 | 55% | 25% | 20% |
| 2008 | 44 | -149 | 830 | 73% | 18% | 9% |
| 2009 | 44 | -244 | 1531 | 77% | 18% | 5% |
| 2010 | 44 | -21 | 159 | 59% | 23% | 18% |
| 2011 | 44 | -110 | 481 | 59% | 18% | 23% |
| 2012 | 44 | -105 | 564 | 66% | 16% | 18% |
| 2013 | 44 | -113 | 257 | 80% | 11% | 9% |
| Period | 308 | -101 | 730 | 67% | 19% | 15% |

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802 **Table 4. Actual share and share under optimal reallocation of land use according to DEA problem (B)**
 803 **that would have complied with the CAP's '2 or 3 crop rule', 2007-2013**

| Year | Actual share | Estimated share for DEA problem (B) | Gains in share from optimal reallocation |
|--------|--------------|-------------------------------------|--|
| 2007 | 52% | 77% | +25% |
| 2008 | 52% | 89% | +36% |
| 2009 | 61% | 98% | +36% |
| 2010 | 57% | 80% | +23% |
| 2011 | 55% | 73% | +18% |
| 2012 | 57% | 82% | +25% |
| 2013 | 68% | 93% | +25% |
| Period | 57% | 84% | +27% |

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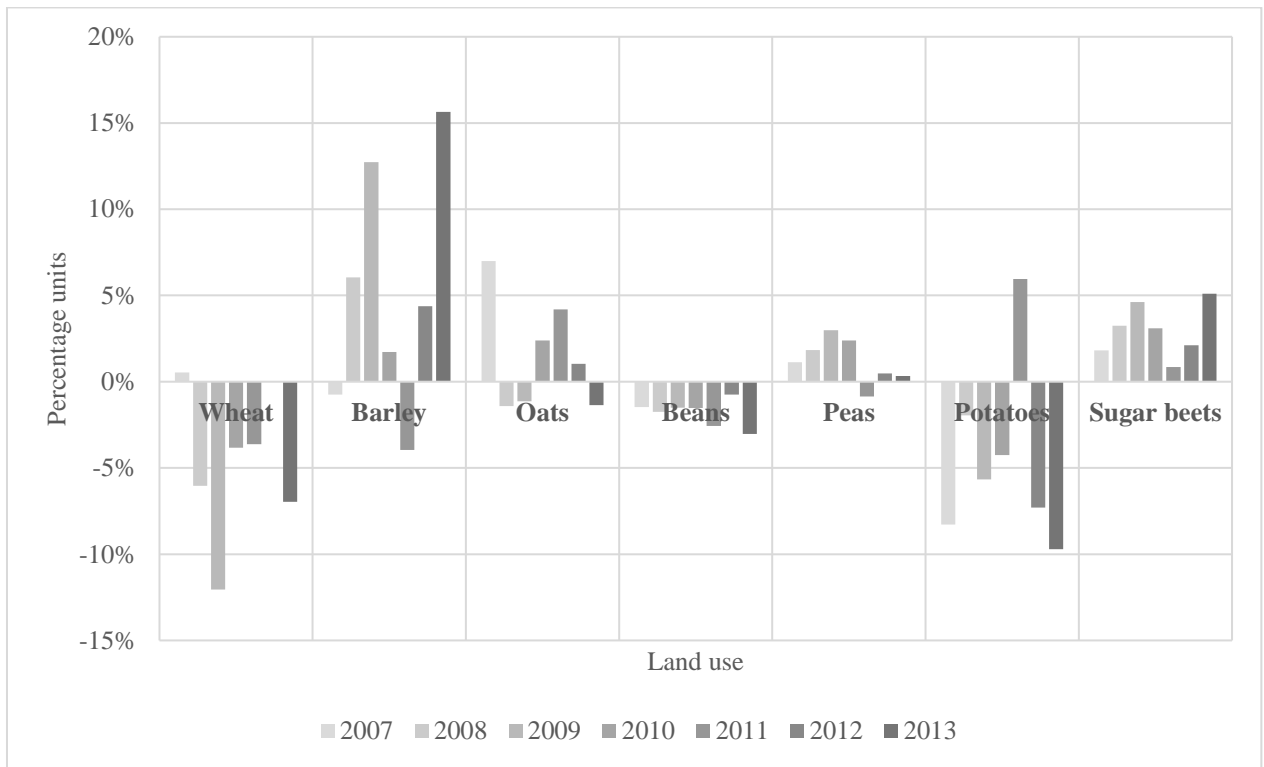
806 **Table 5. Opportunity costs of the Shannon index for crop diversification per 0.1 ha using the directional**
 807 **distance function approach, 2007-2013**

| Year | Number of farms | Average (in constant 2007 £) | Std. Dev. (in constant 2007 £) | Share | | |
|--------|-----------------|------------------------------|--------------------------------|----------|-----|----------|
| | | | | Negative | 0 | Positive |
| 2007 | 44 | 49 | 125 | 0 | 27% | 73% |
| 2008 | 44 | 22 | 68 | 0 | 52% | 48% |
| 2009 | 44 | 37 | 50 | 0 | 48% | 52% |
| 2010 | 44 | 65 | 151 | 0 | 64% | 36% |
| 2011 | 44 | 110 | 330 | 0 | 66% | 34% |
| 2012 | 44 | 61 | 169 | 0 | 16% | 84% |
| 2013 | 44 | 212 | 941 | 0 | 61% | 39% |
| Period | 308 | 79 | 391 | 0 | 48% | 52% |

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810 **Figures**



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812 **Figure 1. Change in land use required for dynamic profit maximisation, 2007-2013 (in percentage units)**