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Evaluating Agri-Environmental Schemes –
The Marginal Costs of Ecosystem Services

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Abstract

We provide a new approach for assessing the cost of marginal ecosystem changes and the effectiveness of agri-environmental schemes. The approach is based on a theoretical and empirical analysis of the bio-economic production interactions between marketed outputs and non-marketed ecosystem services at the micro level. To frame the economic nature of the problem, we employ a generalized joint production model in combination with cost minimization. The generalized joint production framework allows for the consideration of complementary, substitutive and competitive relationships between agricultural production and non-marketed ecosystem services generation and avoids double counting. From this theoretical model we distinguish three theoretical cases depending on the imposed minimum acceptable level of the non-marketed ecosystem services. We employ farm level panel data for the UK to empirically investigate these cases. More specifically, to represent and evaluate the production structure, we estimate first- and second-order elasticities derived from a flexible transformation function. Results show that the majority of farms produce agricultural output and ecosystem services in a complementary relationship. Generation of multiple ecosystem services on the same farm showed either a substitutive or competitive relationship. A change in the composition of the ecosystem services output would have very different implications for individual farms.

Keywords: agri-environmental services, bio-economic modelling; economies of scale and scope

JEL codes: Q18, Q57, Q58.

1. INTRODUCTION

Farmland plays a critical role in the provision of many ecosystem services (ES) in addition to providing traditional consumptive benefits (food, fiber and fuel). The list of ES that agriculture envelopes has grow to include such things as carbon sequestration, energy conservation, wildlife habitats of various kinds, scenic views and cultural heritage, along with water and air quality. Whereas the ES per unit area might be lower than that of unmanaged ecosystems such as wetlands and forests, the fact that some 40 % of the Earth land area is used for farming purposes emphasises the potential total contribution (Foley *et al*., 2005). In recognition of the value associated with the non-marketed ES services, agri-environmental agreements are receiving increasing attention as a means to enhancing (reducing) the supply of environmental public goods (bads) associated with agricultural activities. Such schemes offer "green" payments (incentive payments and /or cost share) or to encourage agricultural producers to voluntarily adopt farming methods that enhance (reduce) the supply of environmental public goods (bads). However there is an increasing debate as to whether programs as currently implemented actually deliver the expected outcomes (*e.g*., Kleijn and Sutherland, 2003; 2006; Pullin and Knight, 2009; Hodge and Reader, 2010).

We see three main challenges: how to make the concept of non-marketed ES operational, how to take into account that many non-marketed ES are produced jointly or simultaneously with agricultural goods, and how to derive detailed supply (marginal cost) functions for the non-marketed ES across a heterogeneous landscape. In the recent literature most attention has been focussed, and progress made, with the first issue. For example, Boyd and Banzhaf (2007) and Fisher *et al*. (2009) define and classify ecosystem services in a way useful for environmental decision making and policy. In addition, both theoretical and normative studies have investigated the second issue of the interrelation of ES and agricultural commodities (Havlík *et al*., 2005; Wossink and Swinton, 2007). Absent however are studies for the third issue, that is empirical work on the supply and opportunity costs of ES associated with agro-ecosystems (except for Peerlings and Polman, 2005). The dearth of marginal cost and supply studies is in sharp contrast in particular to the growing literature on the societal relevance and valuation of these same ES (e.g., Porter *et al*., 2009). Although knowledge of how ES affect human wellbeing is important, understanding and modelling the underlying processes leading to service *provision* is essential for predicting and managing change in ES (Nicholson *et al*., 2009).

The provision of ES in agricultural ecosystems depends on both the biophysical heterogeneity across the landscape and on farm management but how these factors interact to affect ES output and composition is still poorly understood. The general understanding is that a further integration of ecological and social sciences research into policy relevant decision modelling would allow ‘better’ choices to be made. Here ‘better’ means cost-efficient, so targets set by public demand are met at minimum cost — efficient environmental management maximises the benefits gained for the money spend given a limited budget (Rashford and Adams, 2007; Fisher *et al*., 2008).

Against this background the overall research question of our paper is as a follows: How to determine the cost of marginal ecosystem changes and the effectiveness of green payments based on a theoretical and empirical analysis of the bio-economic production relationships at the micro (farm) level. Identification of ES supply functions of agro-ecosystems depends on the knowledge of the relationships between marketed and non-marketed ES, and assessment of direct cost and opportunity costs at the margin. These opportunity costs vary by the green things considered and across farms, reflecting local and farm–specific conditions. Thus supply curves should be estimated at a low level of aggregation accounting for biophysical and socio-economic variability.

Our paper contributes to the literature as follows. First, the approach in our paper is based on several non-marketed ecosystem services simultaneously and in conjunction with agricultural production. To gain insights into the nature of the problem, we employ a generalized joint production model in combination with cost minimization. The generalised joint production framework allows for the consideration of complementary, substitutive and competitive relationships between marketed and non-marketed benefits generated by agro-ecosystem services. We implement the generalised joint production framework empirically as a transformation function. To the best of our knowledge, no similar empirical study in the context of agricultural ES has been reported in the economics literature. Our paper is also different from Omer *et al*. (1997) who address whether technology change over time has contributed to ES from agro-ecoystems.

Second, we include farm/farmer specific impacts and use panel data analysis. Armsworth *et al*. (2009) emphasise how panel data analysis in particular could serve as an analytical bridge between ecology and the social sciences. Whereas this statistical method is common in applied micro economics and also in other areas (such as evidence based medicine) it has not been taken up by ecologists. Panel data modelling offers a solution to the problem of bias caused by unobserved heterogeneity, a common problem in the fitting of models with cross-sectional data sets from non experimental settings. This means that our approach differs from standard work on the evaluation of conservation practices. Ecological studies that address farmland ES commonly use controlled experiments and parsimonious models. The focus is typically on the response to one conservation activity under specific environmental conditions and much of this experimental work has been undertaken to investigate the response of biodiversity to changes in land use activity. Because of resource and design constraints, ecological field programs can only cover a limited amount of environmental variation. Meta-analysis of the results of several of such experiments has been suggested but such methods are still premature in practice (Ferraro and Pattanayak, 2006; but see Kleijn *et al*., 2009). In addition and importantly, ecological experiments typically address only the ecological effects and do not look at the opportunity costs of the conservation activity.

Third, as an empirical example we apply our approach to farm level panel data for the U.K., a country where an ecosystem approach to land use is being widely discussed and promoted by governmental and non-governmental agencies (Sutherland et al., 2006). We consider the Environmental Stewardship Scheme (ESS) and the Hill Farm Allowance (HFA). Main objective of both ESS and HFA is to secure ES benefits at levels above those of the minimum acceptable cross-compliance conditions applying for income-support payments through the Single Payment Scheme under the EU's Common Agricultural Policy[1]. The ESS seeks to bring a large proportion of farmland across the country under agri-environmental agreements by offering a wide range of management options from which farmers 'earn' points towards a minimum per farm (based on size). In contrast the HFA is spatially targeted and has a fixed set of management regimes.

The results of the random effects estimation of the flexible transformation function reveal that the majority of farms in our sample produce agricultural output and ecosystem services in a complementary relationship. The combined generation of different ecosystem services on the same farm show either a substitutive or competitive relationship. We also find that a change in the composition of the ecosystem services output would have very different implications for individual farms. This corresponds well with the concerns and debate about the proposed reformulation of the HFA program as an ESS program for the Uplands in the UK.

We proceed as follows. The next two sections introduce the theory and hypotheses followed by the empirical method and the data, after which we report the results of the statistical analysis and discuss our findings. In the conclusion, we elaborate on the implications of our findings for policy analysis and for further research on agri- environmental regulation.

2. ECOSYSTEM SERVICES AND AGRICULTURE

We limit our analysis to the role of ES in agro-ecological systems. Specifically we look at the role of these ES in the decision context of agri-environmental schemes. In line with Boyd and Banzhaf (2007), we treat ES as ecological phenomena. An important distinction is that services and benefits are not identical — services only generate benefits in a situation of demand. Thus ES are the aspects of agro-ecological systems utilised (actively or passively) to produce human well-being. These services do not have to be directly utilised. We agree with Fisher *et al*., (2009) that delineating between intermediate services, final services and benefits might be the best we can. It is unlikely we will have the capacity or knowledge to measure of all the interactions and dependencies between ecosystem components and processes.

Farm practices vary widely in the level of public and private externalities they generate. Although properly managed lands can have beneficial effects on ecosystem functioning, many studies have documented the substantial negatives impacts of agriculture on various ecosystem services. Thus the combination in which ES and marketable outputs are generated is not fixed but depends on the specific farm practices used. Figure A1 in the appendix shows to two sets of practices (production possibility frontiers) in profit and ES space. When visualised as a production possibility frontier the ES-dimension of agricultural production exist both in the negative and the positive quadrant (Chouinard *et al*., 2008). Whether a certain profit is obtained with positive or negative public ES is an empirical question depending on farming practices available and local conditions.

In agro-ecosystems some final ES are produced with marketed outputs as accidental by-products or externalities. This latter category includes regulatory ES like water quality (which could be a beneficial ES or a harmful disservice, in the instance of water pollution), landscape appearance, net carbon sequestration, or wildlife habitat provision. In addition, certain ES provide intermediate products in the agricultural production process that have market value because they contribute directly to output of marketable farm products. This category includes such ES as soil nitrogen fixation, soil aeration, pollination by wild pollinators, and pest control by natural enemies. Most of these essential services have parallel input markets, and they have monetary value to farmers that can be calculated from the marketed input replacement cost. Multiple ES can represent different facets of the same underlying ecosystem, and hence treating them independently can lead to potential double counting of benefits or the overlooking of synergy in ES provision. Because some ES are produced with agricultural goods or have a intermediate role in agricultural production, ES provision by agriculture does not neatly fit the standard wisdom that non-marketed ES will fail to be produced (Wossink and Swinton, 2007; Nicholson *et al*., 2009).

In summary: agriculture offers special opportunities for ES provision and management because of economies of scale and scope. It follows that only those farm practices that generate net positive public ES should be rewarded by positive policy incentives. In addition, positive incentives should not be used, or reduced accordingly, when farmers employ specific land use practices because of the associated immediate effects on agricultural production (see Pannell, 2008, p. 228-229). This means that a reference line of 'reasonable practice' needs to be set up. The reference line would indicate where the Polluter Pays Principle ends and the Beneficiary Pays Principle starts. This reference line depends critically on the available farming practices and the given biophysical conditions in which these are used.

3. THEORETICAL MODEL

To gain additional insights into the nature of the problem, we employ a generalised joint production model in combination with cost minimization. This theoretical model serves three purposes: to further formalise in economic terms the interaction of private production activities and ES, to formulate testable hypotheses, and to motivate an empirical approach.

The relationship among outputs discussed in section 2 above should dictate the economic model to describe ES generation. It follows that a joint production framework is inadequate. This type of analysis assumes the two outputs (ES and agricultural production) are inseparable and share all inputs. This provides too little flexibility to describe accurately the externalities from production. On the other hand, a multi-product specification with independent production functions provides too much flexibility to be useful in analysing the interaction of agricultural production activities and ES.

The positive/negative externality (ES) interacts with agricultural production which emphasises the importance of allowing for weak separability (Archibald, 1988; Weaver, 1996; De Koeijer et al., 1999). The two outputs are produced simultaneously but since these are multiple outputs a separate production function is used for each output. This leads to a generalised joint production model. First applied to externalities by Buchanan (1966) this model allows for joint inputs and the possibility of varying the proportion of agricultural output and ES. Omitting the time aspect, for a specific location with given biophysical and geographical characteristics *D* the model can be written in implicit form as:

$$F(Y, X, Z; D) \leq 0 \tag{1a}$$

$$G(Z, X; D) \leq 0 \tag{1b}$$

where *Y* is the vector of agricultural outputs (e.g., food provisioning), *Z* is the vector of final agro-ecosystem services and *F(.)* and *G(.)* are their production functions. *X* denotes a vector of inputs, contributing simultaneously to *Y* and *Z*. Combinations of *Z* and *Y* are site specific due to the physical environment as reflected in *D*, the vector of the a-biotic and biotic factors beyond a farmer's control. In addition, the combination in which the Y and Z are generated is not fixed but depends on the farmer's production decisions about *X* and *Y*. The equations enable the integration of two alternative perspectives, one where ecosystem services are associated with input use and the other were they take the form of outputs. The generalized joint production framework permits consideration of complementary, substitute and competitive relationships between marketed output and non-marketed ES. To assess these economic trade-offs, equations (1a) and (1b) are extended to a cost minimization framework. This also allows determination of the required level of incentives to be offered in order to stimulate the provision of ES by the individual farmer. Cost-minimization is less restrictive in terms of mathematical conditions than profit-maximization. For profit-maximization, the production functions of the two outputs must be strictly concave downwards; else a profit maximizing point cannot ever be reached. Strict concavity is not necessary for cost-minimization and this in turn allows for inferior inputs (see Silberberg and Suen, 2000, Chapter 8). These are important advantages as will be shown below. In addition, no adjustment is required to a free-market level of the price of the agricultural output.[2]

In order to establish the marginal cost of trading-off Y for Z, it will be necessary to impose a constraint on the level of ecosystem services, Z_{min} , which can be imagined to have been imposed by a benevolent social planner. Summarizing the aspects above, the economic solution is found through minimizing the direct cost function subject to the constraint on the ecosystem services, Z_{min}:

$$Min_X \quad \{C = pX - c\} \tag{2a}$$

$$s.t. \quad F(X, Z; D) \geq Y \tag{2b}$$

$$G(X, D) \geq Z_{\min} \tag{2c}$$

where the fixed costs of the fixes factors of production are denoted as c and the price of the inputs is denoted as p. Y is a parametric value of marketable agricultural outputs, that is we derive the solution that minimizes total cost for arbitrary levels of the agricultural output without deciding what output level will be chosen by the farmer on the basis of profit maximization (Silberberg and Suen, 2001). Assuming the existence of an interior solution, the first order conditions for an optimal solution are given by:

$$-p + \lambda_1 F_X + \lambda_2 G_X = 0 \tag{3}$$

$$F(X, Z; D) - Y = 0 \tag{4}$$

$$G(X; D) - Z_{\min} = 0 \tag{5}$$

where λ_1 is the Lagrange multiplier for the technology constraints (2b) and λ_2 is the Lagrange multiplier for the constraint on ecosystems services (2c). In eqn. (3), the marginal effect of input use on agricultural output, F_X , is composed as follows:

$$F_X = \frac{\mathrm{d}F}{\mathrm{d}X} = \frac{\partial F}{\partial X} + \frac{\partial F}{\partial Z}\frac{\partial Z}{\partial X}$$

(6)

where $\partial F/\partial X$ denotes the direct effect of input use and $\partial F/\partial Z$ *($\partial Z/\partial X$) denotes the indirect effect of input use on marketable output Y by way of the ecosystem services. Input bundle X contributes to both agricultural output and to ecosystem services, $\partial F/\partial X \geq 0$ and $\partial G/\partial X \geq 0$. Based on the discussion in section 2 and Figure A1, we assume that Z becomes an inferior input for the production of the agricultural output once a specific level Z_1 of ES has been reached. Thus $\partial F/\partial Z \geq 0$ for $Z \leq Z_1$ and $\partial F/\partial Z < 0$ for $Z > Z_1$.

Under the assumption that the functions F and G are sufficiently well behaved so that the second order conditions for a constrained minimum are satisfied, the solutions of the first order conditions yield the indirect cost function:

$$C^*(Y, Z_{\min}) = pX^* + c \tag{7}$$

We are particularly interested in how this minimum cost function will respond to a change in the minimal acceptable level of ecosystems services. Using the envelope theorem and the first order conditions above, this shadow price can be formulated as:

$$\frac{\partial C^*}{\partial Z_{\min}} = \lambda_2^* = \frac{p - \lambda_1^* F_{X*}}{G_{X*}} \tag{8}$$

Eqn. (8) shows how the generation of ES and agricultural production is connected through technical interdependencies and non-allocatable inputs. When the optimal amount of input X^* yields insufficient ES to satisfy $Z_{\min}$, a rearrangement in input use, ∂X^*, is required to generate more ES, see Eqn. (5). This rearrangement in input use, ∂X^*, affects output Y, see Eqn. (6). We can now distinguish three cases:

- *Case 1* (Complementary). Both the direct yield effect, $\partial F/\partial X$, and the indirect yield effect, $\partial F/\partial Z$ *($\partial Z/\partial X$), from the change in input use are positive (but decreasing). Thus a marginal increase in Z will enhance commodity output Y. In this situation the shadow price of the constraint on ES is nil, $\lambda^*_2 = 0$. This situation is represented by $Z_{\min} < Z_2$ in Figure A1.
- *Case 2* (Substitutive). Either the direct yield effect, $\partial F/\partial X$, , or the indirect yield effect, $\partial F/\partial Z$ *($\partial Z/\partial X$), is non-positive but the net yield effect of the rearrangement of input X is positive, see Eqs. (6) and (8). The shadow price of the constraint on ES remains nil, $\lambda^*_2 = 0$. In figure A1, this would be $Z_2 \leq Z_{\min} \leq Z_1$.
- *Case 3* (Competitive). Further reallocation of inputs X is not possible without a net loss in yield. The direct yield effect of reallocating X is nil and there are yield losses caused by the required increase in Z needed to satisfy the constraint on the ecosystem services. In this case there is a shadow price of the constraint on ES, $\lambda^*_2 > 0$, made up of the expenditures for the additional inputs X and the net loss in yield. This situation is represented by $Z_{\min} > Z_2$ in Figure A1.

From the theoretical discussion it follows that the prevalence of Cases 1-3 is an empirical matter that depends on: (a) the site-specific physical environment, (b) the type of agricultural production as reflected in the production function *F*, and on (c) the specific level of $Z_{\min}$ that is imposed.

Practitioners, farmer and the policy maker alike, can be expected to be interested in the extent of Case 1 and 2 where the supply of ES incurs no cost. This trajectory is subject to heterogeneity — it will vary by type of farms and by biophysical and geographical characteristics.

4. EMPIRICAL APPLICATION

Agri-environmental policies that pursue non-marketed ES are a combination of incentive-based policies and command and control. Payments are offered for a number of approved farm practices (options) that can be easily monitored and that aim at an increase in specific final agro-ecological system services. The European Rural Development Regulation dictates that payment for these practices must be no more than the income forgone plus the additional costs incurred from undertaking environmental management. In practice, scheme payments are calculated using national average gross-margin figures with average commodity/input price forecasts for the next 5 year. The use of national averages inevitably means that the payments may over or under compensate an agreement holder which obviously is inefficient.

Our empirical analysis considers two agri-environmental programs: the Environmental Stewardship Scheme (ESS) and the Hill Farm Allowance (HFA). The ESS is a voluntary, non-competitive, ‘whole-farm’ scheme to encourage farmers across a wide area of farmland to deliver simple environmental management. The ESS was launched in 2005 and comprises Entry Level Stewardship (ELS) and Higher Level Stewardship. Organic farms are eligible for Organic Entry Level Stewardship and Organic Higher Level Stewardship. The ESS is an example of the ‘wide-and-shallow’ approach replacing the more targeted schemes that were in place since the mid eighties (Dobbs and Pretty, 2008). By September 2007, more than 47% of the total farmed area in England was enrolled in the entry level ESS. The area under the organic stewardship entry level is small, some 6% relative to the area under ELS (DEFRA, 2008). Thus most relevant in practise is the ELS in which participants can choose from a wide range of over 50 management options. These options include for example hedgerow management, stone wall maintenance, low input grassland, buffer strips, and arable options. ELS payment is £30 per ha for all the land entered into the scheme. In return participants are required to deliver 30 points (8 points in Less Favoured Areas) worth of management options per ha of land in the scheme. There is no minimum holding size for entry into ESS and agreements are five year minimum which is an EU requirement.

The Hill Farm Allowance (HFA) is also voluntary and non-competitive and rewards hill farmers and land managers in Severely Disadvantaged Areas (SDAs) for the delivery of environmental and landscape benefits, through a series of specially designed upland options. The HFA scheme recognises the difficulties that farmers face in the English uplands which are highly valued for their biodiversity, contribution to drinking water quality and flood mitigation and as a part of the natural cultural heritage. Participants must have a minimum of 10 hectares of eligible SDA forage land, and agree to keep it in agricultural production, continuously. They also need to keep eligible breeds of sheep and/or cows at a minimum of 0.15 livestock units per hectare across the LFA area of the holding. HFA is based on area payments (£/ha), which are made at different rates for different types of land and size of holding. For example in 2006, the payment for SDA Non-Moorland was £24.82 per ha for 0-350 ha and £12.41 for 350-700 ha. The Hill Farm Allowance is currently in flux and will likely be replaced by an Uplands ESS . The form this should take is subject to debate.

There are considerable differences between the ESS and the HFA that we expect will bear out in our empirical evaluation. Most of the 50+ management options included in the ELS part of the ESS are generic and the scope for variation from the average of £30 of income foregone and additional costs are therefore considerable. There is a low uptake of certain options and a significant proportion of agreement holders choose a limited number of options. The choice of options often does not match well with policy priority options for a given area (Chaplin, 2009). In addition, there is significant sectoral and associated geographical variations in the level of ELS agreement uptake. In contrast, the HFA is targeted geographically and prescriptive in terms of management.

The empirical analysis employs farm level data based on the Farm Business Survey annually collected by DEFRA, UK. Our extracted sample consisted of all farms participating in the ESS scheme across England and Wales in the years 2005 to 2007. Data for 2008 and 2009 was not yet available at the time we completed this study. Our final sample consisted of 393 observations relating to 251 farms. Each farm is in the sample for at least 2 years with the majority of observations for 2007 (214). The sample farms are located all over England and Wales and about 5% is organic. The average farmer is 52 years of age, is male and has at least a college or national diploma certificate.

Descriptive statistics can be obtained from the authors upon request. The average farm in the sample generates about 64% of its annual total output from agricultural activities, income from ecosystem services accounts for about 7% (ranging from about 0.4 to 30%). Cultivated area is 175 ha with 150 units of livestock. The variable EES covers payments received for participation in the Environmental Stewardship Scheme, our dataset does not distinguish between Entry Level Stewardship, Organic Entry level of Higher Level Stewardship.[3] Following Peerlings and Polman (2004) we used the ESS payments and HFA payments received as a proxy measure of the production of ecosystem services on the individual farm. Thus our outputs include: agricultural output (YAO), two types of ecosystem services (ZESS and ZHFA) and other non-agricultural output (YNAO). Inputs are land, labor, capital, lifestock, machinery, fertilizers, pesticides, purchased feed and veterinary services. Capital covers landlord type capital exclusive of agricultural land. All agricultural monetary variables, including the agri-environmental payments were deflated applying the appropriate PPI published by UK National Statistics. We used 2005 as the base year.

Our empirical analysis considers both agricultural outputs and environmental services and a transformation function is desirable for modeling the production process. The consideration of multiple outputs (i.e. agricultural output, output from environmental services as the Environmental Stewardship Scheme and the Hill Farm Allowance Scheme, non-agricultural and non-environmental service related output) precludes the estimation of a production function. In addition, we wish to avoid the disadvantages of normalizing by one input or output as would be required for a distance function. Imposing linear homogeneity on an input (output) distance function requires normalizing the inputs (outputs) by the input (output) appearing on the left hand side of the estimating equation. This raises issues about what variable to choose as the numeraire and about econometric endogeneity because the right hand side variables are expressed as ratios with respect to the left hand side variable (Coelli, 2000). A common approach in input distance function-based agricultural studies is to normalize by land that is to express the function in input-per-acre terms (*e.g.*, Paul and Nehring, 2005). However this procedure is ill suited for our application where biophysical variation of the land on the individual farm can be expected to be important.

We thus rely on a transformation function model representing the output producible from a given input base and existing conditions, which also represents the feasible production set. This function in general form can be written as $0 = F(\mathbf{Y},\mathbf{X},\mathbf{T})$, where $\mathbf{Y}$ is a vector of outputs, $\mathbf{X}$ is a vector of inputs and $\mathbf{T}$ is a vector of (external) shift variables. The function reflects the maximum amount of outputs producible from a given input vector and external conditions. By the implicit function theorem, if $F(\mathbf{Y},\mathbf{X},\mathbf{T})$ is continuously differentiable and has non-zero first derivatives with respect to one of its arguments, it may be specified (in explicit form) with that argument on the left hand side of the equation. Accordingly, we estimate the transformation function $Y_1= G(\mathbf{Y_{-1}},\mathbf{X},\mathbf{T})$, where, Y_1 is the agricultural output of the farms (mainly livestock and crops) and Y_{-1} the vector of other outputs (including ecosystem services related outputs $\mathbf{Z}$, and non-agricultural output Y_{NAO}), to represent the technological relationships for the farms in our data sample. Note that this specification does not reflect any endogeneity of output and input choices, but simply represents the technological maximum of Y_1 that can be produced given the levels of the other arguments of the $F(\bullet)$ function. We approximate the transformation function by a flexible functional form (second order approximation to the general function), to accommodate various interactions among the arguments of the function including non-constant returns to scale and technical change biases.

A flexible functional form can be expressed in terms of logarithms (translog), levels (quadratic), or square roots (generalized linear). We used the generalized linear functional form suggested by Diewert (1973) to avoid any problem with mathematical transformations of the original data (e.g. taking logs of variables which would lead to modelling problems with zero values):

$$
\begin{aligned}
Y_{AO} &= F(\mathbf{Z}, Y_{NAO}, \mathbf{X}, \mathbf{T}) \\
&= a_0 + 2a_{0ESS} Z_{ESS}^{0.5} + 2a_{0HFA} Z_{HFA}^{0.5} + 2a_{0NAO} Y_{NAO}^{0.5} + \sum_{k=1}^{K} 2a_{0k} X_k^{0.5} + a_{ESSESS} Z_{ESS} \\
&+ a_{HFAHFA} Z_{HFA} + a_{NAONAO} Y_{NAO} + a_{kk} X_k + \sum_{k=1}^{K} \sum_{\ell=1}^{K} a_{k\ell} X_k^{0.5} X_\ell^{0.5} + \sum_{k=1}^{K} a_{kESS} X_k^{0.5} Z_{ESS}^{0.5} \\
&+ \sum_{k=1}^{K} a_{kHFA} X_k^{0.5} Z_{HFA}^{0.5} + \sum_{k=1}^{K} a_{kNAO} X_k^{0.5} Y_{NAO}^{0.5} + b_T T + b_{TT} TT + \sum_{k=1}^{K} b_{kT} X_k^{0.5} T \\
&+ b_{ESST} Z_{ESS}^{0.5} T + b_{HFAT} Z_{HFA}^{0.5} T + b_{NAOT} Y_{NAO}^{0.5} T \ ,
\end{aligned} \tag{9}
$$

where Y_{AO} is the total agricultural output (identical to Y_1 above); Z_{ESS} denotes total output under the environmental stewardship scheme (ESS), Z_{HFA} is total output under the hill farm allowance (HFA) and Y_{NAO} denotes total non-agricultural output as the components of Y_{-1}. X denotes inputs with X_{LAND}=land, X_{LAB}=labor, X_{CAP} = capital, X_{LU} = livestock units, X_{MACH} = machinery, X_{FERT} = fertiliser, X_{CHEM} = pesticides and X_{FODV} = fodder and veterinarian services. Finally, a time trend is the only component of the **T** vector. The estimated model recognizes each farm i in time period t is as a separate entity and incorporates the following random effects specification:

$$
\begin{aligned}
y_{AO,\ it} &= a_0 + 2a_{0ESS} z_{ESS,\ it}^{0.5} + 2a_{0HFA} z_{HFA,\ it}^{0.5} + 2a_{0NAO} y_{NAO,\ it}^{0.5} + \sum_{k=1}^{K} 2a_{0k} x_{k,\ it}^{0.5} \\
&+ a_{ESSESS} z_{ESS,\ it} + a_{HFAHFA} z_{HFA,\ it} + a_{NAONAO} y_{NAO,\ it} + a_{kk} x_{k,\ it} + \sum_{k=1}^{K} \sum_{\ell=1}^{K} a_{k\ell} x_{k,\ it}^{0.5} x_{\ell,it}^{0.5} \\
&+ \sum_{k=1}^{K} a_{kESS} x_{k,\ it}^{0.5} z_{ESS,\ it}^{0.5} + \sum_{k=1}^{K} a_{kHFA} x_{k,\ it}^{0.5} z_{HFA,\ it}^{0.5} + \sum_{k=1}^{K} a_{kNAO} x_{k,\ it}^{0.5} y_{AO,\ it}^{0.5} \\
&+ b_T t_{it} + b_T t_{it} t_{it} + \sum_{k=1}^{K} b_{kT} x_{it}^{0.5} t_{it} + b_{ESST} z_{ESS,\ ti}^{0.5} t_{it} + b_{HFAT} z_{HFA,\ it}^{0.5} t_{it} \\
&+ b_{NAOT} y_{NAO,\ it} t_{it} + u_{it} \qquad \text{with} \quad u_{it} = \phi_i + e_{it} \ ,
\end{aligned} \tag{10}
$$

The error term $u_{i\ t}$ in the random effects model (10) has a composite structure. The unobservable farm-specific factors are represented by the random variable ϕ_i which is assumed to be distributed with mean zero and standard deviation σ_ϕ; $e_{i\ t}$ is assumed to be distributed with mean zero and standard deviation σ_e. In addition it is assumed that ϕ_i is independent of $e_{i\ t}$ (Baltagi, 1995).

To represent and evaluate the technological or production structure, we are primarily interested in the first- and second-order elasticities of the transformation function. The first-order elasticities (i.e. direct effects) of the transformation function in terms of agricultural output Y_{AO} represent the (proportional) shape of the production possibility frontier (given inputs) for outputs Y_{NAO}, Z_{ESS} and Z_{HFA} and the shape of the production function (given other inputs and Y_{NAO}, Z_{ESS} and Z_{HFA}) for input X_k – or output trade-offs and input contributions to agricultural output respectively. That is, the estimated output elasticity with respect to the "other" outputs: $\varepsilon_{AO,ESS}$=$\partial \ln Y_{AO}/\partial \ln Y_{ESS}$= $\partial Y_{AO}/\partial Y_{ESS}$*$(Y_{ESS}/Y_{AO})$; $\varepsilon_{AO,HFA}$= $\partial \ln Y_{AO}/\partial \ln Y_{HFA}$= $Y_{AO}/\partial Y_{HFA}$*(Y_{HFA}/Y_{AO}), and $\varepsilon_{AO,NAO}$= $\partial \ln Y_{AO}/\partial \ln Y_{NAO}$= $\partial Y_{AO}/\partial Y_{NAO}$*$(Y_{NAO}/Y_{AO})$ are expected to be negative as they reflect the slope of the production possibility frontier, with its magnitude capturing the (proportional) marginal trade-off.. The estimated output elasticity with respect to input k, $\varepsilon_{AO,k}=\partial \ln Y_{AO}/\partial \ln X_k= \partial Y_{AO}/\partial X_k*(X_k/Y_{AO})$, are expected to be positive, with its magnitude representing the (proportional) marginal productivity of X_k. Second-order own-elasticities may also be computed to confirm that the curvature of these functions satisfies regularity conditions; the marginal productivity would be expected to be increasing at a decreasing rate, and the output trade-off decreasing at an increasing rate, so second derivatives with respect to Y_{NAO}, Z_{ESS}, Z_{HFA} and X_k would be negative (concavity with respect to both outputs and inputs).

Returns to scale may be computed as a combination of the Y_{AO} elasticities with respect to Y_{NAO}, Z_{ESS}, Z_{HFA} and the inputs. For the situation of a production function (single output), returns to scale is defined as the sum of the input elasticities to reflect in a sense the distance between isoquants. Similarly for a transformation function such a measure must control for the other outputs. Formally, returns to scale are defined for the transformation function similarly to the treatment for the distance function in Caves et al. (1982) – for our purposes as $\varepsilon_{AO,X}=\sum_k \varepsilon_{AO,k} /(1 - \varepsilon_{AO,ESS} - \varepsilon_{AO,HFA} - \varepsilon_{AO,NAO})$. Technical change is measured by shifts in the overall production frontier over time. As our only technical change variable is the trend term T, productivity/technical change is estimated as the output elasticity with respect to T, $\varepsilon_{AO,T}=\partial \ln Y_{AO}/\partial T= \partial Y_{AO}/\partial T*(1/Y_{AO})$. This represents how much more agricultural output may be produced on an annual basis in proportional terms, given the levels of the inputs and other outputs. Returns to scale and technical change measures may be computed for each observation and presented as an average over a subset of observations (such as for the full sample, a farm, a time period or a particular class of spatially clustered farms), or may be computed for the average values of the data for a subset of observations. The latter approach is known as the delta method; it evaluates the elasticities at one point that represents the average value of the elasticity for a particular set of observations, allowing standard errors to be computed for inference even though the elasticity computation involves a combination of econometric estimates and data.[5]

Based on our theoretical model outlined above the following measures are particularly relevant for our analysis: The direct yield or output effect dF/dx as the marginal product or marginal physical product is the extra output produced by one more unit of an input. Assuming that no other input to production changes, the marginal product of a given input k, MP_k, is captured by the estimated first derivative with respect to input k:

$$MP_k = \partial Y_{AO}/\partial X_k, \tag{11}$$

The total direct yield or output effect, MP_X , as the total marginal product or total marginal physical product is the extra output produced by one more unit of all inputs;

$$MP_X = \partial Y_{AO}/\partial X = \textstyle\sum_k (\partial Y_{AO}/\partial X_k). \tag{12}$$

The estimated marginal effects on Y_{AO} with respect to the "other" outputs are:

$$ME_{AO,ESS} = \partial Y_{AO}/\partial Z_{ESS} \quad (13)$$

$$ME_{AO,HFA} = \partial Y_{AO}/\partial Z_{HFA} \quad (14)$$

$$ME_{AO,NAO} = \partial Y_{AO}/\partial Y_{NAO}\,, \quad (15)$$

whereas the total direct yield or output effect dF/dY-1 is the extra output produced by one more unit of all "other" outputs:

$$TME_{Y-1} = \partial Y_{AO}/\partial Y_{-1} = \partial Y_{AO}/\partial Z_{ESS} + \partial Y_{AO}/\partial Z_{HFA} + \partial Y_{AO}/\partial Y_{NAO} \quad (16)$$

Further we are interested in the indirect yield or output effect with respect to the "other" outputs given marginal changes in input k:

$$IME_{AO,ESS,k} = ME_{AO,ESS}\,(\partial Z_{ESS}/\partial X_k) = (\partial Y_{AO}/\partial Z_{ESS})(\partial Z_{ESS}/\partial X_k) \quad (17)$$

$$IME_{AO,HFA,k} = ME_{AO,HFA}\,(\partial Z_{HFA}/\partial X_k) = (\partial Y_{AO}/\partial Z_{HFA})(\partial Z_{HFA}/\partial X_k) \quad (18)$$

$$IME_{AO,NAO,k} = ME_{AO,NAO}\,(\partial Y_{NAO}/\partial X_k) = (\partial Y_{AO}/\partial Y_{NAO})(\partial Y_{NAO}/\partial X_k) \quad (19)$$

with the total indirect yield or output effect per "other" output (dF/dY-1)(dY-1/dX) caused by the use of one more unit of all inputs as:

$$\Sigma IME_{AO,Y-1,X} = \sum_k (\partial Y_{AO}/\partial Y_{-1})(\partial Y_{-1}/\partial X_k) \quad (20)$$

Given the signs and values of the estimated marginal measures defined by (11) to (20), the following three cases can be distinguished in line with our theoretical outline above: Case I, where the total direct effect, given by (12), is positive and the total indirect effect, given by (20) is also positive; Case II, where either the total direct effect or the total indirect effect is negative but the total net effect is positive (i.e. $\sum_k(\partial Y_{AO}/\partial X_k) + \sum_k(\partial Y_{AO}/\partial Y_{-1})(\partial Y_{-1}/\partial X_k) > 0$); Case III, where both effects are negative and hence the total net effect is negative (i.e. $\sum_k(\partial Y_{AO}/\partial X_k) + \sum_k(\partial Y_{AO}/\partial Y_{-1})(\partial Y_{-1}/\partial X_k) < 0$).

5. RESULTS AND DISCUSSION

The estimated generalized linear transformation function in a random effects specification showed a satisfactory overall model performance (estimates and standard quality measures can be obtained from the authors upon request). Additional diagnostic tests show that the random effects estimation is superior to the ordinary cross-sectional estimation (see LM test value). More than 50% of the estimated parameters are significant at least at the 10% level. Table A1 reports the estimated first order elasticities at the sample means. As required by theory these estimates are positive for the non-primary outputs and negative for all inputs. Further, the own second order elasticities are all negative confirming the curvature correctness of the transformation function estimated. The calculated direct and indirect effects are summarized in Table A2. Note that these values represent the simple statistical means based on the effects calculated for each individual observation in the sample. Next, we used the estimation results to assess which of the three product relationships (complementary, substitutive or competitive) prevails in our dataset based on the procedure outlined in section 4.3 above. We assessed this relationship for: agricultural output, two types of ecosystem services and other, non-agricultural output. The assessment of these product relationships are based on the individual direct and indirect effects at each observation values for outputs and inputs. The results of this assessment are reported in Table A3 with an interpretation of the various cases in Table A4.

Table A3 shows that a majority of 314 (80%) of the 393 farms in our sample produce agricultural output and ecosystem services (either ESS or HFA oriented) in a complementary relationship. A minority of the farms produced these outputs in a competitive relationship (79 observations). We did not find substitutive relationship between the production of ecosystem services and agricultural production. Hence, for most of the farms (80%) the production of agricultural output and the provision of ecosystem services is complementary and so both could be increased further (at the margin) by changing the input allocation. These farms operate on the upward sloping part of the production possibility frontier up to Z_2 in Figure A1.

From the estimation results it follows that current ESS and HFA programs are formulated in such a way that they lead to opportunity costs for only 20% of the farms participating in one of these schemes. This implies the requirements in these schemes could be further increased at no initial cost for 80% of the farms. It would be important to identify and analyse the latter group of farms in terms of location and main activities. The results in Table A3 further reveal that the production of multiple ecosystem services (ZHFA and ZESS) on the same farms shows either a substitutive relationship (121 and 202 observations, respectively) or a competitive relationship (272 and 191 observations, respectively). Thus there is no evidence of complementary relationship for the production of different ecosystem services (ZHFA and ZESS).

The effect of a change in the composition of the generation of different ecosystem services on the same farm is complex.. A change in favour of HFA output would have negative effects for 69% of the farmers. A change in favour of ESS outputs has less clear cut economic effects: for 51 % this would be advantageous and for 49 % negative. This result is interesting in particular in the context of the current reformulation of the HFA scheme. Likely this will take the form of an Upland Higher Level ESS. There is a real concern among farmers and researchers how this change in regulation will play out (Hodge and Reader 2010). The empirical results in Table A3 justify this concern.

Further the results show that agricultural and non-agricultural output are substitutive for the majority of farms in the sample (314) and competitive for only a minority of farms (79 observations). We also found that the nature of the production relationship between ecosystem services and non agricultural output depends on the type of ecosystem service provided: substitutive (202 observations) or competitive (191 observations) for ESS, and complementary (121 observation) or competitive (272 observations) for HFA. Thus for 69 % of the farmers more HFA output combines well with non-agricultural activities but the opposite applies to the remaining 31 %. The interaction between ESS activities and non-farm activities shows a very different pattern — for 51% of the farms this relationship is substitutive.

6. CONCLUSIONS

As ecosystem managers, farmers' decisions drive the mix of ecosystem services and agricultural goods that is produced. Agri-environmental schemes that pursue ecosystem service provision are a combination of incentive-based policies and command and control. Payments are offered for a number of approved farm practices (options) that can be easily monitored. For agri-environmental schemes to be effective and cost-efficient, decision makers need to know how these options interact with agricultural production decisions which means taking into account the heterogeneity in farms and in farming conditions. Spatial heterogeneity, the "where" issue, matters both economically and ecologically. Economically, spatial heterogeneity matters because the economic landscape varies as much as the biophysical landscape. Both these spatial factors affect the marginal costs of producing ecosystem services and thus where changing farming practices is most effective and least costly (selective control).

We provide a new approach for assessing the cost of marginal ecosystem service provision and the effectiveness of green payment schemes based on a theoretical and empirical analysis of the bio-economic production interactions at the farm level. The generalized joint production framework allows for the consideration of complementary, substitutive and competitive relationships between agricultural production and non-marketed ecosystem services generation and avoids double counting. From this theoretical model we distinguish three theoretical cases depending on the imposed minimum acceptable level of the ecosystem services.

Next, we employ farm level panel data for the UK to empirically investigate these cases. More specifically, to represent and evaluate the technological or production structure, we estimate first- and second-order elasticities derived from a flexible transformation function.

Results showed that the majority of farms produce agricultural output and ecosystem services in a complementary relationship but that the nature of the production relationship depends distinctly on the type of ecosystem services provided; a change in the composition of the ecosystem services output would have very different implications for individual farms. There was no evidence of a complementary relationship for the production of different ecosystem services. Generation of different ecosystem services on the same farm showed either a substitutive or competitive relationship.

In further work we aim to investigate significant characteristics of the farms being part of the classes I-III as estimated in our paper. A multivariate (ordered) probit modeling approach could be used to relate the three classes to spatial, socioeconomic, financial, and other individual farm/farmer characteristics. More sophisticated models (mixed-effects logistic) could also be explored. Finally, other modelling alternatives to the two-part model could be used, *e.g.* Generalized Methods of Moments.

ENDNOTES

1. The single-farm payments that replace commodity price support are tied to the condition of maintaining land in good agricultural condition based on national standards of 'Good farming practice'. This condition is commonly known as 'cross- compliance'.
2. Where agricultural policy supports prices foregone revenue will be larger than under free market conditions. Hence, in order to analyze payment for ecosystem services as an alternative to agricultural price support policies, the opportunity cost should be based on the free market.
3. Hodge and Reader (2010) present a detailed analysis of the extent and types of practices that have been adopted using DEFRA's GENESIS GIS system. This material cannot be linked to DEFRA's annual Farm Business Survey used in our study. Neither the GENESIS data nor our data set contains information on the actual environmental impacts.
4. The "delta method" computes standard errors using a generalization of the Central Limit Theorem, derived using Taylor series approximations, which is useful when one is interested in some function of a random variable rather than the random variable itself (Gallant and Holly, 1980). For our application, this method uses the parameter estimates from our model and the corresponding variance covariance matrix to evaluate the elasticities at average values of the arguments of the function.

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Figure A1 – Production possibility frontiers with farm profit and ES

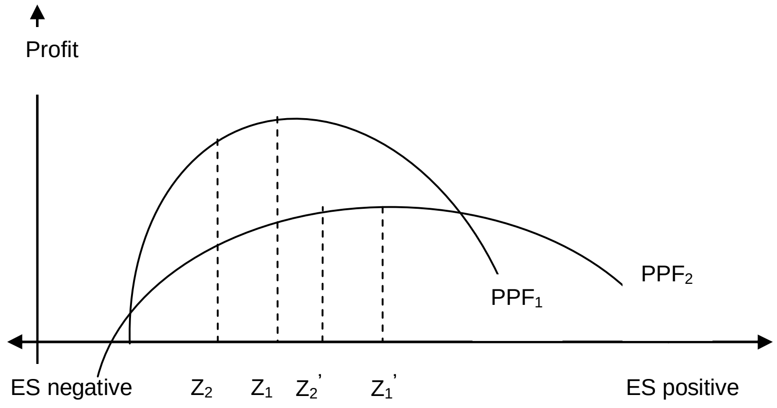

Table A1 – Estimated 1st Order Elasticities

Output/Input	est[1]	se
ESS	-.011***	.005
HFA	-.232***	.043
NAO	-.151**	.079
LAND	.068***	.007
LAB	.281***	.071
CAP	.024***	.003
LU	.638***	.092
MACH	.152***	.064
FERT	.036**	.016
CHEM	.147***	.028
FODVET	.175***	.057
T	.134***	.043
RTS	1.039***	.053

(Delta Method at Sample Means)

[1] : *,**,*** : significance at 10%- , 5%- , or 1%-level.

The own 2nd order elasticities are all negative, the estimates can be obtained from the authors upon request.

Table A2 - Descriptive Statistics for Direct and Indirect Effects

Effect evaluated	Mean	Std. Dev.[1]	Min	Max
dYAO/dX	173.978	259.197	-440.066	1591.110
dYAO/dZESS	.372	2.887	-8.233	12.288
dYAO/dZHFA	-2.529	6.310	-39.071	23.947
(dYAO/dZESS)(dZESS/dX)	0.065	0.032	0.006	0.192
(dYAO/dZHFA)(dZHFA/dX)	0.071	0.058	0.007	0.438
(dYAO/dZESS)(dZESS/dZHFA) = (dYAO/dZHFA)(dZHFA/dZESS)	-6.61e-04	5.61e-04	-0.004	-7.01e-05
(dYAO/dYNAO)(dYNAO/dZHFA)	9.03e-05	7.74E-05	1.21e-05	5.83e-04
(dYAO/dYNAO)(dYNAO/dZESS)	-5.03e-05	3.09E-05	-2.24e-04	5.24e-06
(dYAO/dYNAO)(dYNAO/dX)	-0.008	0.005	-0.043	-7.11e-04

Table A3 - Estimated Cases and number of observations per case for various Product-Product Relationships[a]

	Relationship considered between the following two variables:						
Effect	Agric. output ESS	Agric. output HFA	HFA ESS	ESS HFA	HFA non agric. output	ESS non agric. output	agric. output non agric. output
Direct effect	dYAO/dX	dYAO/dX	dYAO/dZHFA	dYAO/dZESS	dYAO/dZHFA	dYAO/dZESS	dYAO/dX
Indirect effect	(dYAO/dZESS)* (dESS/dX)	(dYAO/dZHFA)* (dZHFA/dX)	(dYAO/dZESS)* (dZESS/dZHFA)	(dYAO/dZHFA)* (dZHFA/dZESS)	(dYAO/dYNAO)* (dYNAO/dZHFA)	(dYAO/dYNAO)* (dYNAO/dZESS)	(dYAO/dYNAO)* (dYNAO/dX)
Case I	**314**	**314**	0	0	121	0	0
Case II	0	0	121	**202**	0	**202**	**314**
Case III	79	79	**272**	191	**272**	191	79
Total Obs.	393	393	**393**	393	**393**	393	393

[a] For variable definition see Table 1. Case I – direct effect and indirect effect are positive (complementary). Case II - direct effect or indirect effect is positive, net effect is positive (substitutive). Case III - direct effect <= 0 and indirect effect is negative (competitive).

Table A4 - Options for Efficient Production Schedule Rearrangements

	Relationship considered between:						
Effect	Agric. output ESS	Agric. output HFA	HFA ESS	ESS HFA	HFA non agric. output	ESS non agric. output	agric. output non agric. output
Case I	**produce more agric. and more ESS output**	**produce more agri and more hfa**	produce more HFA and more ESS	produce more ESS and more HFA	produce more HFA and more non agric.	produce more ESS and more non agric.	produce more agri and more non agri
Case II	produce more agric. or more ESS (depending on effects)	produce more agric. output or more HFA (depending on effects)	produce more HFA or more ESS (depending on effects)	**produce more ESS or more HFA** **(depending on effects)**	produce more HFA or more non agric. (depending on effects)	**produce more ESS or more non agric.** **(depending on effects)**	**produce more agri or more non agri** **(depending on effects)**
Case III	produce more ESS	produce more HFA	**produce more ESS**	produce more HFA	**produce more non agric**.	produce more non agric.	produce more non agric.