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MARKETED OUTPUTS AND NON-MARKETED ECOSYSTEM SERVICES: THE EVALUATION OF MARGINAL COSTS

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Abstract

We provide a new approach for assessing the cost effectiveness of green payment schemes. We allow for complementary, supplementary and competitive relationships between agricultural production and non-marketed ecosystem services generation. Our theoretical model distinguishes three theoretical cases depending on the minimum level of the non-marketed ecosystem services. These cases are empirically investigated using a flexible transformation function and farm level panel-data from the UK. We find that the biophysical connections between the non-marketed ecosystem services and market activities have important implications for marginal costs.

Keywords: ecosystem services; green payments; non-separability; policy evaluation.

JEL codes: Q18, Q57, Q58.

1. Introduction

Farmland plays a critical role in the provision of many ecosystem services in addition to the traditional consumptive benefits (food, fibre, fuel). The list of ecosystem services provided by agriculture has grown to include such things as carbon sequestration, wildlife habitats of various kinds, scenic views and cultural heritage, along with water and air quality. The ecosystem services per unit area of agricultural land might be lower than that of unmanaged ecosystems (such as wetlands and forests) but the fact that some 40 % of the Earth's land area is used for farming emphasises the potential total contribution (Foley *et al.*, 2005). In recognition of this potential, voluntary green payment policies are receiving increasing attention as a means to enhancing the supply of environmental public goods associated with agricultural activities (OECD, 2010). In the European Union in particular there has been a movement towards such programs.

Successive reforms of the European Common Agricultural Policy (CAP) have shifted away from production support by including a parallel agri-environmental policy (Grossman, 2009). Agri-environmental measures, rooted in structural legislation in the 1970s and 1980s, became a more prominent part of the CAP with the MacSharry reform. Regulation 2078/92 formally required each member state to implement an agri-environmental program. A further shift was the Agenda 2000 reform which introduced mandatory cross-compliance for all farmers. The implementation followed with the 2003 Horizontal Regulation. This Regulation makes direct payments conditional on compliance with statuary management requirements imposed by eighteen legislative measures which, applied from January 2005, include the Nitrate Directive, the Wild Birds and Habitat Directive and the Directive concerning the protection of groundwater. In addition, in a separate requirement, member states have the obligation to tie direct payments to maintaining land in good agricultural condition. For this member states must establish minimum standards of ‘Good farming practice’ either regionally or nationally. With Regulation 1698/2005, agri-environmental programs became a mandatory part of the Rural Development Plans in all EU Member States. Farmers may choose to enrol in a contract to carry out one or more management adaptations that go beyond the requirements for cross compliance. Payments are based on the income foregone and additional costs. Agri-environmental programs are now a central element of the second pillar of the CAP both in terms of agricultural area covered and CAP expenditures. However these programs have also become the subject of critical debates. Initially the criticism centred on the environmental effectiveness of the agri-environmental schemes. More recently the cost effectiveness of the schemes is likewise being questioned (see e.g., Matzdorf and Lorenz, 2010; Mettepenningen et al., 2011).

Against this background, the objective of this paper is provide a new approach for assessing the cost effectiveness of voluntary green payment schemes at the farm level. When various ecosystem services are derived from the same agro-ecosystem (farmland) together with agricultural output, changes in their levels are physically connected through the basic biophysical function of the ecosystem. Different services are ‘bundled’ together and thus depend on agricultural production. The production relationships between agricultural output and non marketed ecosystem services may be complementary, competitive or substitutive. This in turn will have an impact on farmers’ opportunity costs and complicates the development of a cost-effective incentive scheme (see Wossink and Swinton, 2007). Few empirical studies have analysed the marginal cost and supply of ecosystem services as joint outputs of the farm despite the importance of the issue and the wide policy interest. The dearth of empirical work on opportunity costs is in contrast with the growing literature on the societal relevance of these same ecosystem services.

Most studies on ecosystem services and agriculture consider these services as inputs or as separate outputs. Many studies demonstrate how basic micro economic theory can be implemented in the situation where the ecosystem service is a productive input (intermediate service) through the production function approach and the expected damage function approach. The physical effect is assessed of changes in an ecosystem service on an economic activity and then valued in terms of the corresponding change in marketed output of the relevant activity (e.g., Barbier, 2007; Klemick, 2010). A related body of previous literature considers ecosystem services purely as outputs (final public environmental goods) and investigates the trade-off with commodity production. The few studies that consider jointness are predominant normative and rely on bio-economic modelling. Early studies investigate minimum necessary compensation payments needed to achieve the provision of such public environmental goods through simulation with farm level optimization models (Hanley et al., 1998; Wossink et al., 1999). More recent simulation studies have assessed economic-ecological tradeoffs at the landscape scale and account for spatial heterogeneity as well as various ecosystem services (e.g., Rashford and Adams, 2007; Nelson et al., 2009). Other studies have extended this normative work to the efficiency of spatially differentiated programs when enforcement is costly or when spatial connectivity has special ecological advantages (e.g.; Antle et al., 2003; Lankoski et al. 2010; Dreschler et al., 2010). Few studies have used an econometric, revealed preference approach. Lubowski et al. (2006) model land use elasticities employing detailed panel survey data and constructed county level estimates of annual returns for specific land uses. The supply function of the public good (i.c. carbon sequestration) is then derived from the simulated changes in land use based on the procedure developed by Stavins (1999). The study by Peerlings and Polman (2004) employs a micro-econometric profit model that treats the private good and the public good as strictly joint outputs to provide insights into the existence and distribution of (dis-) economies of scope associated with producing the outputs jointly versus separately. The supply function for the public good follows from the estimated shadow price equation of the public good which differs for individual producers.

Previous analyses as discussed above have limitations when it comes to the marginal cost of ecosystem services that interact with commodity output and are produced simultaneously with agricultural goods. Integrated normative ecological-economic models run in practical modelling difficulties due to the gaps in the understanding of the complexity and interconnectedness of biophysical interactions and the role of the intermediate services (Polasky and Segerson, 2009). In addition such normative studies assume land use decisions are based on the immediate pecuniary returns only and leave out the actual farm setting. Econometric revealed preference studies address some of these concerns but necessarily rely on the opportunity cost of alternative land use. This covers the situation of land retirement programs for permanent environmental or cultural purposes but is less suited for the analysis of the voluntary adoption of practices on working land that remains in agricultural production. The econometric joint production approach has another major limitation; the perspective of strict jointness does not fit the services provided by a working ecosystem because of the underlying biophysical structure.

Our paper contributes to the literature as follows. We allow for complementary, supplementary and competitive production relationships between agricultural outputs and ecosystem services at the farm level. We implement this theoretical model empirically as a transformation function. This function estimates the multi-input, multi-output production relationship needed to capture the effect of altering a bundle of inputs to get a changed bundle of outputs including both marketed agricultural outputs and non–marketed ecosystem services. Using the estimated model, individual producers can be classified based on the relationship between marketed and non-marketed outputs. This enables the calculation of opportunity costs of ecosystem service for the individual farm and an assessment of the cost-effectiveness of green payments. To the best of our knowledge, no similar empirical study in the context of agricultural ecosystems services as been reported in the economics literature. Most directly related is the study by Peerlings and Polman (2004) but these authors do not evaluate the range of (complementary, supplementary and competitive) production relationships as analysed in the present study.

As an empirical example we apply our approach to farm level panel data for the U.K. In this country an ecosystem approach to land use is promoted by governmental and non-governmental agencies but there is an increasing concern about the effectiveness of the working land programs that have been implemented since 2003 (Hodge and Reader, 2010). With flat rate payments set at the national level, and thus not accounting for differences in opportunity costs, agreement holders are likely to be under or over compensated (Fraser, 2009; Quillérou and Fraser, 2011). We consider the Environmental Stewardship Scheme (ESS) and the Hill Farm Allowance (HFA). Main objective of both ESS and HFA is to secure ecosystem services at levels above those of the cross-compliance conditions for income-support payments through the Single Payment Scheme under the EU’s Common Agricultural Policy.

The results of the fixed 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 supplementary or competitive relationship. We also find that a change in the composition of the ecosystem services output would have different implications for individual farms. This corresponds well with the concerns and debate about the reformulation of the HFA program as an ESS program for the Uplands in the UK (Acs, 2010).

We proceed as follows. The next section introduces 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 agricultural production

Ecosystem services are the aspects of ecological systems utilized (actively or passively) to produce human well-being. As emphasised by Boyd and Banzhaf (2007), ecosystem service and benefits are not identical – ecosystem services are ecological phenomena and not the benefits obtained from ecosystems as such. Services only generate benefits in a situation of demand. These services do not have to be directly utilized and in fact many are intermediate and contribute to multiple final services. For example water regulation can contribute to human benefits from sanitation, recreation, crop irrigation and hydroelectric power generation.

For a further understanding of their characteristics and functioning, ecosystem services are commonly divided into regulating, provisioning, cultural and supporting services (MEA, 2005; Fisher et al., 2009). Regulation services result from the capacity of agro-ecosystems to regulate climate, hydrological and bio-chemical cycles, earth surface processes, and a variety of biological processes. Provisioning services relate to the production of food, fibre and fuel. Cultural, or information, services relate to the benefits from agro-ecosystems through recreation, cognitive development, relaxation, and spiritual reflection. Finally, the supporting services, including soil formation, photosynthesis, nutrient and water cycling, represent the web of biotic and abiotic processes that underlie the functioning of the agro-ecosystem.

Building on the insights above, it follows that agriculture and ecosystem services are interrelated in at least three ways as visualised in Figure 1 (see Dale and Polasky, 2007; Zhang et al., 2007). First, agriculture's main contribution is through the provisioning services (e.g., food, fibre, fuel) but, in addition, it can also generate other beneficial ecosystem services. Important cultural, recreational and aesthetic services from agriculture include landscape appearance and wild species appreciated by sightseers. These services have no market value to farmers, so if they are produced it is because of farmers' personal preferences or as accidental by-products or externalities. Second, agriculture requires many regulating ecosystem services as inputs to production. At the same time, agriculture also provides regulating ecosystem services such as pollination, soil retention, and biological pest control and water regulation. Because these regulating services are instrumental to the functioning of the agro-ecosystem, they have dual roles. They serve as inputs and as complementary outputs to provisioning ecosystem services. Most of these regulating services have parallel input markets, and they have monetary value to farmers that can be calculated from input replacement cost or value of productivity changes. Third, ecosystem services from agriculture may have negative effects. Farmers apply inputs in order to ensure that crops and livestock grow rapidly (nutritional inputs) and healthily (pest management inputs). The type and levels of input use and outputs generated affect the characteristics and the significance of environmentally critical processes (water balance and purification, regulation of erosion and sedimentation, and wildlife habitat). This can lead to disservices such as euthrophication and the loss of biodiversity and cultural values.

Agriculture generates a certain amount of non-marketed ecosystem services because these are produced together with agricultural goods or they have an intermediate role in agricultural production (Hodge, 2000; Nelson et al., 2009). An obvious policy question is then how this compares to the amount of ecosystems services society feels should standard be provided by agricultural land and how the interrelation with agricultural production affects the farm level costs of the supply of these ecosystem services. To gain a theoretical economic understanding of this policy question, Figure 2 visualises the cross-compliance standard for good farming practice, Z_o, and the joint production of agricultural output and ecosystem services. The ecosystem services dimension of agricultural production exists both in the negative and the positive quadrant. Figure 2 is limited to the positive quadrant because of the research focus of the present analysis.

The three panels in Figure 2 illustrate the three principal potential product-product relationships of the classic model for the production of multiple products: competitive, complementary and supplementary. Competitive products involve a trade-off such that more of one cannot be produced without less of the other. This is illustrated by the decreasingly concave production possibilities frontier as in the first panel of Figure 2. Complementary products can be produced in increasing quantities shown by the backward bending portion of the production possibility frontier in the second panel. In this panel up to A the ecological system contributes to the production of the private good. Finally a product is supplementary if some positive level of this product is possible without any reduction in the level of the other product output. This is shown by the portion Z_0-A of the PPF in the third panel of Figure 2.

The joint production of agricultural goods and non-marketed ecosystem services implies a technical interdependency: this interlinking is such that (some) inputs cannot be assigned to either of the two outputs (Shumway et al., 1984). Jointness in functional terms and complementarity, competitiveness or supplementary in terms of the production possibility set need not be incompatible. The provision of individual ecosystem services (e.g., soil fertility) may be typical of one product-product relationship but each farm can provide multiple services and these by themselves are produced in non separable bundles. The relationship of interest here is that between agricultural output and the ‘sum total’ of the ecosystem services provided through various farm-level activities (for which farmers receive payment). The joint production of agricultural outputs and this sum total of the ecosystem services at the farm level is commonly characterized as having a complementary-competing production possibility frontier, meaning that when one of the outputs (say the agricultural output) is receiving low levels of the shared input, the two outputs are complementary but that at higher levels of the agricultural output they become competitive (Hodge, 2000, p. 265; Havlík et al., 2005, p. 494). The supplementary product-product relationship is subsumed as a special intermediate situation involving a complementary and a competitive effect.

Based on this theoretical exposition we can now distinguish three cases for the opportunity cost of participation in an agri-environmental scheme as represented by a constraint on ecosystem services, Z_1:

- Case I (Complementary). A marginal increase in ecosystem services beyond Z_1 will enhance commodity output. Thus the shadow price of the constraint on ecosystem services is nil. Many examples can be given, such as the cultivation of cover crops which contribute to erosion control and soil fertility enhancement.
- Case II (Supplementary). The rearrangement of input to meet the marginal increase in ecosystem services beyond Z_1 leads to a negative direct effects on agricultural output but to a compensating positive indirect effect via an increase in (regulating) ecosystems services. The shadow price of the constraint on ecosystem services remains nil. This outcome corresponds for example to the situation

where farm land, labour and machinery inputs are dedicated to field margin habitats which offer refugia for beneficial insect species as pollinators or pest predators that increase crop production on the rest of the farm.

- Case III (Competitive). A reallocation of inputs is not possible without a net loss in agricultural output. Thus in this case there is a shadow price of the constraint on ecosystem services. Such a competitive relationship would occur with for example the allocation of land to specific conservation purpose such as in-field ponds.

The classification of a sample of farmers into the Cases I-III enables an assessment of the opportunity costs of marginal ecosystem changes. Practitioners, farmers and policy makers alike can be expected to be interested in the extent of Cases I and II where marginal increases of ecosystem service provision incurs no opportunity costs. This information in turn can be used to evaluate the cost-effectiveness of existing green payment schemes. A marginal increase in the provision of ecosystem services is necessarily costly for the individual farmer who is under-compensated for the income foregone of the specific amount of ecosystem services provided. In contrast, producers who are overcompensated could, at the margin, produce more ecosystem services without incurring cost.

The prevalence of Cases I-III is an empirical matter that depends on the amount of ecosystem services generated in combination with the shape of the production possibility frontier for the sample farms. This shape depends on the biophysical and socioeconomic heterogeneity across the agricultural landscape (e.g., differences in farm size, soil types and management capacities). Once sample farms have been classified into the Cases I-III, further investigation of common characteristics of the farms in each category can provide insights in for example regional variation and differences in land use that could contribute to improve the cost effectiveness of existing schemes.

The classification of a sample of producers into the Cases I-III needs to take into account scale effects and test for non-concavity of the function defined by the surface of the production possibility frontier. This is because complementary product relationships (Case I) fit the general definition of economies of scope. Economies of scope mean that joint production is cheaper than production separately. Scope economies however can be due to scale effects, convexity effects as well as product complementarities (Chavas and Kim, 2007). Scale effects imply that the production possibility frontier expands more than proportionally with an increase in the resource base so that larger farms produce relatively more ecosystem services per unit input (for example land). Convexity effects imply a violation of the traditional diminishing rate of transformation. In line with the limited research available, figure 1 assumes dome-shaped production possibility frontiers but this relationship could potentially exhibit non-concavities (Brown et al., 2010; Chavas and Di Falco, 2011).

3. Study region, data and empirical model

3.1. Background

Prices paid (set) by a regulatory agency to reward the generation of ecosystem services serve as signals for relative adjustments in the farmers' production plans. The focus of this empirical study is on how scheme design affects producers' output-output decisions over space and time. Hence, prices paid for ecosystem related outputs are the accurate measure to approximate underlying relationships as experienced by the farmer. The "true price" for ecosystem services might be different and consequently the "true amount of ecosystem services provided" could differ. Such a "true price" would require large-scale cost and time intensive ecological effects studies of the link between a precise ecological effect (across space and time) and a specific marginal change in the production plan of an individual farmer (at a specific location and time). Such a link will however likely never be precisely established due to complex ecological processes and structures that are involved (Polasky and Segerson, 2009).

Our empirical analysis considers two agri-environmental programs in the UK: the Environmental Stewardship Scheme (ESS) and the Hill Farm Allowance (HFA). 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. In contrast the HFA is spatially targeted and has a fixed set of management regimes.

The ESS is the main agri-environmental scheme in the UK since 2005. It is a non-competitive, 'whole-farm' scheme and there is no minimum holding size for entry. The aim is to encourage farmers to deliver simple environmental management that goes beyond the Single Payment Scheme of the CAP and its requirement to maintain land in Good Agricultural and Environmental Condition. Its primary objectives are to: conserve wildlife (biodiversity), maintain and enhance landscape quality and character, protect the historic environment and natural resources, promote public access and understanding of the countryside, and protect natural resources. The policy is implemented at the national level through agri-environmental schemes that offer payments for a number of approved practices (options) that can be easily monitored and that aim at an increase in specific final agro-ecological system services. These options include for example hedgerow management, stone wall maintenance, low input grassland, buffer strips, and arable options; a detailed overview of the ELS management options is presented in Hodge and Reader (2009). Payment is uniform although benefits and compliance cost are spatially heterogeneous. 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 ESS comprises Entry Level Stewardship (ELS) and Higher Level Stewardship. By September 2007, more than 47% of the total farmed area in England was enrolled in the ELS. ELS relies on self-selection by farmers of environmental options from a wide range of (over 50) management options, each option corresponding to a given number of points reflecting the agricultural income foregone (nationally estimated). The point minimum for ELS participation is 30 points per ha and 8 points for Less Favoured Areas (LFA). This translates into a payment of £30 per ha (£8 for LFA). The second tier or Higher Level Stewardship targets more complex management and capital work plans with applications competitively selected by Natural England, the operating authority. Scoring of HLS applications is spatially differentiated, based on areas of the English countryside with similar landscape character, each with a specific association of wildlife and natural features with priority given to Sites of Special Scientific Interest (SSSIs) and Scheduled Monuments (Quillérou et al., 2011). Organic farms are eligible for Organic Entry Level Stewardship and Organic Higher Level Stewardship. The area under the organic stewardship entry level is small, some 6% relative to the area under ELS (DEFRA, 2008).

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 faced by sheep and cattle farmers in the English uplands and their vital role in maintaining a landscape that is highly valued for its biodiversity, contribution to drinking water quality and flood mitigation and as a part of the natural cultural heritage. The HFA system is based on area payments (£/ha). At the time of our study the HFA was in flux and to be replaced by an Uplands Higher Level Environmental Stewardship Scheme (see also Acs et al., 2010).

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 per ha 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. In contrast, the HFA is targeted geographically and prescriptive in terms of management.

3.2 Data

The empirical analysis employs farm level data based on the Farm Business Survey annually collected by the Department for Environment, Food and Rural Affairs (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.

Central to our analysis is the perspective of opportunity cost of producing ecosystem services at the level of the individual farm based on tradeoffs and synergies between the various outputs on the farm. Thus our outputs include: total agricultural output (Y_{AO}), other non-agricultural output (Y_{NAO}) and two types of ecosystem services output (Z_{ESS} and Z_{HFA}). Inputs are land, labour, capital, livestock, machinery, fertilizers, pesticides, and purchased feed and veterinary services. Table 1 provides summary statistics.

Agricultural output Y_{AO} is total revenue generated from agricultural activities and thus combines livestock and crop products which can potentially create a bias in the estimation results. Degrees-of-freedom constrained the inclusion of separate livestock and crop revenue variables and the related cross-effects in the empirical model. One aggregated agricultural revenue measure was considered justified as the share of livestock production is only minor for the farms in the sample and price changes are controlled to a certain degree by adequate deflating measures. Other non-agricultural output Y_{NAO} is total revenue from non-agricultural activities.

The ecosystem services outputs, Z_{ESS} and Z_{HFA}, are measured as the payments received at the farm level similar to agricultural output (Y_{AO}) and non-agricultural output (Y_{NAO}). As discussed in section 3.1, in the ELS system each of 50+ management options earns points per unit towards points per farm in total, e.g., 400 points per ha with 4 m buffer strip; 12 points per tree or 0.22 per m of hedgerow. Hodge and Reader (2010) show that by September 2007 the options that accounted for most points purchased were Permanent Grassland with Low Inputs with 15.0 million points bought and Hedgerow Management on both side of hedge with 13.5 million points bought, followed by other hedge options. The arable option with greatest adoption, by points, was Over-wintered stubbles with 6.7 million points bought, followed by 6m Buffer Strips with 5.2 million points. Individual management plans also accounted for large numbers of points with Soil Management Plans and Nutrient Management Plans accounting for 7.1 and 4.8 million points. It has to be emphasised that the study by Hodge and Reader is based on a different data source that is incompatible with the DEFRA's annual Farm Business Survey used in our study and that neither the data used by Hodge and Reader nor our data set contains information on the actual environmental impacts.

For participation in the HFA scheme, 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. The HFA area payments (£/ha) 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.

Land input in ha is utilized agricultural area as defined by Farm Business Survey collected by DEFRA annually. Labor input is hours per year full-time equivalent labour use on farm. Total capital refers to landlord type capital but excluding land related items and covers milk quota, buildings, drainage, improvements and woodland. Livestock input is livestock units and machinery input refers to machinery related capital both as defined by Farm Business Survey. Fertilizer input is total expenses on fertilizer items; pesticide inputs refers to total expenses on crop protection chemicals, and fodder and veterinary input is total expenses on related items all as defined by Farm Business Survey collected by DEFRA annually. All agricultural monetary variables, including the agri-environmental payments are in £ per year and were deflated applying the appropriate PPI published by UK National Statistics. We used 2005 as the base year.

In addition several variables were used to proxy farmers' individual production environment. These include: nitrate vulnerable zone: binary variable, the farm is mostly located in a nitrate vulnerable zone or not; organic production: binary variable, if the farm produces organic or not; less favoured area 1: binary variable, if the farm area is (partly) located in a severely disadvantaged area (SDA) based on land quality criteria; less favoured area 2: binary variable, if the farm area is (partly) located in a disadvantaged area (DA) based on land quality criteria; altitude 1: binary variable, if the farm area is mostly located at an altitude between 300 and 600 m; altitude 2: binary variable, if the farm area is mostly located at an altitude over 600 m; age: continuous variable, the age of the farm manager. We trust that these additional variables and the use of panel data controls satisfactorily for potential endogeneity with respect to output and input choices as a consequence of land quality and climatic heterogeneity. Data on land quality and climatic heterogeneity at the plot level (i.e. GIS based information) is currently not available for all the plots/regions included in the data sample.

3.3 Empirical model specification

For the estimation we rely on a transformation function incorporating multiple outputs and inputs. A transformation function represents the output producible from a given input base and existing conditions, which also represents the feasible production set. The transformation function in general form can be written as $0 = G(\mathbf{Y},\mathbf{X},\mathbf{T})$, where $\mathbf{Y}$ is a vector of outputs, $\mathbf{X}$ is a vector of inputs and $\mathbf{T}$ is a vector of variables representing the external production environment which can not be influenced by the optimisation decisions of the individual farmers.

The transformation function $0 = G(\mathbf{Y},\mathbf{X},\mathbf{T})$ reflects the maximum amount of outputs producible from a given input vector and external conditions. By the implicit function theorem, if $G(\mathbf{Y},\mathbf{X},\mathbf{T})$ 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 $Y_1= H(\mathbf{Y_{-1}},\mathbf{X},\mathbf{T})$, where, Y_1 is the agricultural output of the farms (mainly livestock and crops) and Y_{-1} the vector of all other outputs (including ecosystem services related outputs and non-agricultural output), 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 H(•) function.

In the transformation function the outputs are specified in levels, thus avoiding econometric endogeneity possibly arising from having the dependent variable (the numeraire output or input) also appear in the arguments of the function. Thus the specification of a transformation function does not require normalizing by one input or output. The latter is typical in distance function (output ratio) specifications in order to impose homogeneity but may violate standard independence assumptions (Felthoven and Morrison Paul, 2004, p. 623). A common approach in input distance function-based agricultural studies is to normalize by land that is to express the function in input-per-hectare terms. However this procedure is ill-suited for our application where hectarage on the individual farm can be expected to be important.

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. 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):

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

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. The vector T includes beside 'time' (as an indicator for technological change), the proxy variables mentioned in section 3.2 , namely 'nitrate vulnerable zone', 'organic production', 'less favoured area 1' and 'less favoured area 2', 'altitude 1' and 'altitude 2', and 'age'.

The estimated model recognizes each farm *i* in time period *t* is as a separate entity and incorporates the following one-way fixed effects specification (see Baltagi, 1995):

$$
\begin{aligned}
y_{AO,\ it} &= a_0 + 2a_{0ESS} z_{ESS,\ it}{}^{0.5} + 2a_{0HFA} z_{HFA,\ it}{}^{0.5} + 2a_{0NAO}\ y_{NAO,\ it}{}^{0.5} + \sum_{k=1}^{K} 2a_{kk} x_{k,\ it}{}^{0.5} \\
&+ a_{ESSESS} z_{ESS,\ it} + a_{HFAHFA}\ z_{HFA,\ it} + a_{NAONAO}\ y_{NAO,\ it} + \sum_{k=1}^{K} a_{kk} x_{k,\ it} + \sum_{k=1}^{K} \sum_{\ell=1}^{K} a_{k\ell} x_{k,\ it}{}^{0.5} x_{\ell,it}{}^{0.5} \\
&+ \sum_{k=1}^{K} a_{kESS} x_{k,\ it}{}^{0.5} z_{ESS,\ it}{}^{0.5} + \sum_{k=1}^{K} a_{kHFA} x_{k,\ it}{}^{0.5} z_{HFA,\ it}{}^{0.5} + \sum_{k=1}^{K} a_{kNAO}\ x_{k,\ it}{}^{0.5} y_{AO,\ it}{}^{0.5} \\
&+ \sum_{t=1}^{T} b_T\ t_{it} + \sum_{t=1}^{T} b_T\ t_{it} t_{it} + \sum_{t=1}^{T} \sum_{k=1}^{K} b_{kT} x_{\ it}{}^{0.5} t_{it} + \sum_{t=1}^{T} b_{ESST} z_{ESS,\ ti}{}^{0.5} t_{it} + \sum_{t=1}^{T} b_{HFAT}\ z_{HFA,\ it}{}^{0.5} t_{it} \\
&+ \sum_{t=1}^{T} b_{NAOT}\ y_{NAO,\ it} t_{it} + \lambda_i + u_{it}
\end{aligned} \qquad (2)
$$

where λ_i is the unknown intercept for each farm (i.e. farm-specific intercepts). We alternatively estimated a random effects specification and used different tests to verify the robustness of our specification. Table 2 (last column) reports the results of a generalized Hausman testing procedure; this test takes also into account potential bias as a consequence of small sample size. The Hausman test results indicates a large and significant difference between the two estimators, hence, we can reject the null hypothesis that both estimators yield similar coefficients in favour of the alternative hypothesis. This results in the conclusion of a more consistent fixed effects estimator for our sample.

Approximating multi-output multi-input production structures by a primal transformation function has the crucial advantage that price information is not needed as shown in eqn. (2) (see e.g. Chambers, 2001). However, some input decisions may imply or determine other decisions on relative input quantities especially with respect to land/acreage decisions (see e.g., Lankoski and Ollikainen, 2003; Romstad, 2009). Consequently, biased estimates because of potential input endogeneity might occur. Only a dynamic estimation of the production problem can satisfactorily address this issue but a critical limiting factor in practice is data availability (Antle, 1983). Panel data regression as above enables to control for unobserved input endogeneity to the extent that it captures that farmers adjust their inputs in response to unobserved time-invariant conditions.

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 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. Thus 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 X_k, $\varepsilon_{AO,k}=\partial \ln Y_{AO}/\partial \ln X_k= \partial Y_{AO}/\partial X_k*(X_k/Y_{AO})$, is expected to be positive, with its magnitude representing the (proportional) marginal productivity of X_k.

For theoretical consistency (i.e. functional regularity conditions) to hold for a transformation function the estimated function has to be concave in both inputs and outputs. This can be tested for by checking the sign of the second derivates with respect to all other outputs and inputs. Hence, 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) (Sauer and Morrison-Paul, 2011).

Based on our theoretical model outlined above, there are several measures of particularly relevance for our analysis. First, 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*:

$$MP_k = \partial Y_{AO}/\partial X_k, \tag{3}$$

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

$$MP_X = \partial Y_{AO}/\partial X = \sum_k (\partial Y_{AO}/\partial X_k). \tag{4}$$

Third, the estimated marginal effects on Y_{AO} with respect to the “other” outputs:

$$ME_{AO,ESS} = \partial Y_{AO}/\partial Z_{ESS} \tag{5}$$

$$ME_{AO,HFA} = \partial Y_{AO}/\partial Z_{HFA} \tag{6}$$

$$ME_{AO,NAO} = \partial Y_{AO}/\partial Y_{NAO}\ , \tag{7}$$

with the total direct yield or output effect dF/dY-1 as the extra output produced by one more unit of all “other” outputs:

$$TME_{Y-1} = \partial Y_{AO}/\partial Y_{-1} = \partial Y_{AO}/\partial Z_{ESS} + \partial Y_{AO}/\partial Z_{HFA} + \partial Y_{AO}/\partial Y_{NAO} \tag{8}$$

Fifth, we are interested in the indirect yield or output effect with respect to the “other” outputs given marginal changes in input k:

$$\mathrm{IME}_{AO,ESS,k} = \mathrm{ME}_{AO,ESS}\,(\partial Z_{ESS}/\partial X_k) = (\partial Y_{AO}/\partial Z_{ESS})(\partial Z_{ESS}/\partial X_k) \tag{9}$$

$$\mathrm{IME}_{AO,HFA,k} = \mathrm{ME}_{AO,HFA}\,(\partial Z_{HFA}/\partial X_k) = (\partial Y_{AO}/\partial Z_{HFA})(\partial Z_{HFA}/\partial X_k) \tag{10}$$

$$\mathrm{IME}_{AO,NAO,k} = \mathrm{ME}_{AO,NAO}\,(\partial Y_{NAO}/\partial X_k) = (\partial Y_{AO}/\partial Y_{NAO})(\partial Y_{NAO}/\partial X_k) \tag{11}$$

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:

$$\Sigma\mathrm{IME}_{AO,Y\text{-}1,X} = \sum_k (\partial Y_{AO}/\partial Y_{-1})(\partial Y_{-1}/\partial X_k) \tag{12}$$

Given the signs and values of the estimated marginal measures defined by (3) to (12), the following three cases can be distinguished in line with our theoretical outline above: Case I, where the total direct effect, given by (4), is positive and the total indirect effect, given by (12) 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. $\sum_k(\partial Y_{AO}/\partial X_k) + \sum_k(\partial Y_{AO}/\partial Y_{-1})(\partial Y_{-1}/\partial X_k) < 0$).

The measures defined by eqns. (3) - (12) above may be computed for each observation and then 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 using the Delta method (Oehlert, 1992).

4. Results and Discussion

The estimated generalized linear transformation function in a fixed effects specification showed a satisfactory overall model performance. The standard model quality measures are reported in Table 2A. Additional diagnostic tests showed that the fixed effects estimation is superior to the ordinary cross-sectional estimation (see LM test value). More than 75% of the estimated parameters are significant at least at the 10% level.

Table 2A further presents the parameter estimates of the production structure. As our measures of interest are combinations of these estimates, a detailed interpretation of all the coefficients in Table 2A is beyond the purpose of our investigation. However it needs some further explanation why the estimates on ESS (a_{0ESS}) and HFA (a_{0HFA}) are of opposing signs and why a_{0LAND} is negative. Note also that $a_{HFALAND}$ is positive and significant while $a_{ESSLAND}$ is much larger in magnitude and insignificant. As for any flexible functional form (i.e. including also second order own and interaction terms) the individual estimates can not be meaningfully interpreted. This can only be done by analysing the first and second order marginal effects as well as variables' elasticities. Hence, we have estimated the various second order elasticities related to the two agri-environmental programs we are investigating and also those related to land (see Table 2B). According to these estimates, we find that the cross second order elasticities of the agri-environmental programs' related outputs both show a negative sign. This means that a marginal increase in the output generated under either agri-environmental program results in a marginal decrease in the output generated under the other agri-environmental program. These values are valid at the sample means only and are based on an estimation using the delta method. With respect to the estimates for land, we find positive and significant cross second order elasticities of the output of both agri-environmental programs with respect to the input land. This means that a marginal increase in the amount of land used results in a marginal increase in the output associated with either agri-environmental program. Again, note that these values are valid at the sample means only and are based on an estimation using the delta method.

The first results to evaluate are the first order elasticities of the estimated transformation function at the sample means reported in Table 3. These first-order output elasticities reflect output tradeoffs and marginal input contributions. As required by theory these estimates are negative for the non-primary outputs and positive for all inputs. Table 3 also presents the returns to scale which is positive as expected. Further, the own second order elasticities (available from the authors) are all negative confirming the curvature correctness of the transformation function estimated. This implies concavity of the transformation function.

The output elasticities in Table 3 with respect to ESS, HFA and NAO reflect the (proportional) marginal trade-off between the outputs. The estimate of -0.169 for ESS shows that producing one percent more ESS output, given input use, would involve 0.169 percent less agricultural output on average for the farms in our sample. In comparison, producing HFA output is slightly more restrictive as reflected in an elasticity of minus 0.188. The elasticity of YAO to livestock inputs (LU) is higher than to other inputs. This might be a reflection of the impact of the UK milk quota system in the sample period (Colman, 2000).

The estimated direct and indirect marginal effects are summarized in Table 4. Note that these total direct and indirect marginal effects are estimated from the perspective of the primary agricultural output and are thus not the same as the second-order own and cross elasticities of Table 2B. Nevertheless, the estimates are consistent. The results in Table 4 show a mean positive direct effect of ESS on agricultural output which suggests economies of scope. On average the increase in ecosystem services of one ESS-point (equivalent to an increase in payment at the farm level of one Pound Stirling) is associated with £0.481 more agricultural output. In contrasts, the direct effect of HFA on agricultural output is negative on average with a wider spread among individual observations. These different results are as expected as the two schemes involve different practices with the HFA scheme offering considerably less flexibility. The direct effect of a marginal change in all inputs on agricultural output YAO is about £227 but this result has a large standard deviation; the minimum observed is minus £672 and the maximum £2485.

Table 4 further shows the results for a series of indirect effects. The indirect effects of one unit change in inputs via the ecosystem service outputs ZESS and ZHFA, that is (dYAO/dZESS)(dZESS/dX) and (dYAO/dZHFA)(dZHFA/dX) respectively, are positive across all observations in the sample. The indirect effect via the ecosystem output ZESS is £0.061 on average with a standard deviation of £0.031. For the ecosystem service output ZHFA this amounts to £0.060 with a standard deviation of £0.051. Thus the indirect effects of ZESS and ZHFA are similar in magnitude and distribution. Notice that these indirect effects, (dYAO/dZESS)(dZESS/dX) and (dYAO/dZHFA)(dZHFA/dX), are very small in comparison with the direct marginal effects of input use on agricultural outputs, dYAO/dX. The same applies for the direct and the indirect marginal effects of HFA and ESS on agricultural output via non-agricultural output YNAO.

Thus the general conclusion from Table 4 is that the direct marginal effects dominate the indirect marginal effects. Next, we used the estimated marginal effects at each individual observation and the procedure outlined in section 3.3 to combine the direct and indirect effects. This enables us to assess the three product-product relationships (complementary, supplementary or competitive) for our dataset. The results are reported in Table 5. Table 5 gives the product relationship for: agricultural output, both types of ecosystem services and other, non-agricultural output.

Table 5 shows that a majority of 310 (79%) 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 (83 observations). We did not find supplementary relationship between ecosystem services and agricultural production. Hence, for most of the farms (79%) the production of agricultural output and the provision of ecosystem services is complementary. From these results it follows that based on both direct and indirect effects, current ESS and HFA programs are formulated in such a way that they lead to opportunity costs at the margin for only 21% of the farms participating in one of these schemes. At first glance this would suggest that the requirements in these schemes could be further increased at no initial cost for many farms. However the 310 farms might be operating right on the margin when accounting for farm level transactions costs. Transactions costs incurred by participants are not explicitly compensated. In this case they must be absorbed by the compensation payments available in the absence of altruism on the part of participants (see Falconer, 2000). From this perspective the 79% of the sample with a complementary relationship for ecosystem services is merely a reflection that payments are based on “the agricultural income foregone (nationally estimated)” and exclude the private transactions costs of scheme participation.

The results in Table 5 further reveal that when both direct and indirect effects are taken into account, the production of multiple ecosystem services (ZHFA and ZESS) on the same farm shows either a supplementary relationship (121 and 202 observations, respectively) or a competitive relationship (272 and 191 observations). There is no evidence of a complementary relationship between the outputs. A change in favour of HFA output would have negative impacts for 69% of the farms. A change in favour of ESS outputs would be neutral for 51% of farms but would be negative for the remaining 49%. This result is interesting in the context of the reformulation of the HFA scheme as an Upland Higher Level Environmental Stewardship Scheme. There is concern among farmers and researchers how this change in regulation will play out in terms of farm economics (Acs et al., 2010). The empirical results in Table 5 justify this concern.

Further the results show that agricultural and non-agricultural output are supplementary for the majority of farms in the sample (310) and competitive for only a minority of farms (83 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: supplementary (202 observations) or competitive (191 observations) for ESS, and complementary (121 observation) or competitive (272 observations) for HFA. Thus for 31% of the farmers more HFA output combines well with non-agricultural activities but the opposite applies to the remaining 69%. The interaction between ESS activities and non-farm activities shows a very different pattern — for 51% of the farms this relationship is supplementary.

An intriguing feature of the results in Table 5 in that the same numbers are showing up in multiple relationships. Inspection confirmed that these are indeed the same farms. Thus the 310 and 83 farms in both the second and third column of Table 5 are identical to the 310 and 83 farms in the final column of this table. Similarly, the fourth and sixth column of Table 5 show the same two groups of 202 and 191 farms. To better understand this symmetry, we return to Table 4 and compare the magnitude and signs of the specific direct and indirect marginal effect. The last two columns of Table 4 show for example that the indirect effects (dYAO/dZESS)(dZESS/dX) and (dYAO/dZHFA)(dZHFA/dX) are positive for all observations. In contrast, the indirect effect represented by dYAO/dYNAO)(dYNAO/dX) is negative for all farms in the sample. From this it follows that the 310 observations with a positive direct effect, dYAO/dX, will be classified as Case I for the product-product relationships of YAO and ZESS or ZHFA but as Case II for the relationship between YAO and YNAO. The 83 observations with a negative direct effect, dYAO/dX, are classified as Case III for both relationships. The allocation of the 121 and 272 farms in Table 5 can be explained in a similar way. Returning to Table 4, we see that the indirect effect of ZHFA via YNAO, that is (dYAO/dYNAO)/(dYNAO/dZHFA), is strictly positive whereas this is not the case for the indirect effect via ZESS, that is (dYAO/dZESS/(dZESS/dZHFA). This explains the 134 observations allocated to Case I for the relationship between ZHFA and YNAO and to Case II for ZHFA and ZESS, respectively. In summary: due to the differences in magnitude, the direct effects dominate the result and this leads to the symmetry in Table 5.

Finally, with green payments schemes set at the national scale but implemented locally, we expected specific patterns to emerge in the region and type (dairy vs. crop) of farms included in the various categories in Table 5. The distribution of the variables used in the estimation however revealed no obvious pattern by category. Next, we investigated additional farm level information including region, rurality and off-farm income but could not distinguish clear patterns in location, geophysical or other characteristics between farm categories.

In terms of the debate about the cost-effectiveness of the working land programs in UK, our results confirm that in improvement might be possible, particularly based on the percentage of Case I farms in Table 5. However without any obvious patterns emerging from our initial investigation, it is unlikely that identification of these farms is straightforward and high transaction costs could be incurred in a more targeted approach to the voluntary working land programs.

5. Conclusions

Agri-environmental schemes as those investigated in or paper pursue ecosystem services through a combination of incentive-based policies and command and control. Payments are offered for a number of approved practices (options). For such 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 farming conditions. The specific challenges encountered in research to support this type of agricultural policy are manifold: First there are the data requirements at a very low level of aggregation (i.e. at plot and/or farm level). Such data, if available at all, are time intensive and sometimes costly to obtain. In addition, issues of confidentiality constrain many possible applications (see e.g. Sauer and Walsh, 2010). Secondly, the statistical modelling has to be of adequate sophistication to deliver a scientifically valid, theoretically sound and empirically robust analysis. Panel data analysis has considerable advantages in this respect but means that research can only be conducted, and result made available, after several years. Finally, the results have to be presented in an accessible format to be effectively communicated to the policy audience and other stakeholders and this needs to be done in a timely and cost-effective way. These different aims are at times mutually exclusive and this has to be kept in mind by the analyst.

In this paper we have presented a new approach for assessing the marginal cost of marginal ecosystem service provision and the effectiveness of existing voluntary schemes based on a theoretical and empirical analysis of the bio-economic production interactions at the farm level. We show that simply calculating the cost of providing ecosystem services based on separate evaluations can lead to misleading results. Central to our analysis is the perspective of opportunity cost of producing ecosystem services taking into account the joint production of ecosystem services and marketed outputs at the level of the individual farm. From this theoretical model we distinguished three theoretical cases depending on the ecosystem services output generated, the site specific biophysical conditions and the production system. We employed a flexible transformation function and farm level panel data from the UK for the empirical assessment. To evaluate the production structure, we estimated first- and second-order elasticities derived from the flexible transformation function. We find that the biophysical connections between the provision of ecosystem services and market activities have important implications for the marginal costs.

The majority of farms in the UK sample produce agricultural output and ecosystem services in a complementary relationship but the nature of the production relationship depends on the agri-environmental scheme through which these services are provided; a change in program participation would have very different implications for individual farms. There was no evidence of a complementary relationship for participation in the two agri-environmental schemes included in the analysis. Note that these results do not reveal the production relationship between individual ecosystem services (e.g., soil fertility, carbon sequestration, water quality, cultural heritage and scenic views) but rather relate to the bundles of ecosystem services targeted by the specific schemes.

Finally, the results suggest that there is potential for efficiency improvement. This could be achieved by a greater emphasis on targeting and by offering contracts on the basis of competitive bidding. To investigate the scope of targeting, further work would be needed to investigate in more detail significant characteristics of the farms in Cases I-III in our paper. A multivariate (ordered) probit modelling approach with endogenous selection could be used to relate the three classes to spatial, socioeconomic, financial, and other individual farm/farmer characteristics. Competitive bidding could allow a more direct reduction of the problem of overcompensation of farmers. This would clearly enhance the cost effectiveness of public spending for public goods but would involve the trade-off of a considerable administrative effort.

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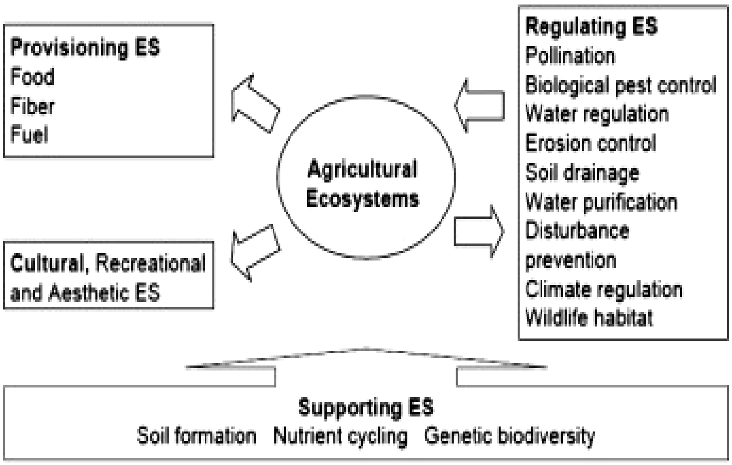
Figure 1 — Relationships between ecosystem services (ES) and agriculture



Source: Ma and Swinton (2011).

Figure 2 – Production possibility frontiers with agricultural output and ecosystem services (ES) and opportunity cost of ES provision

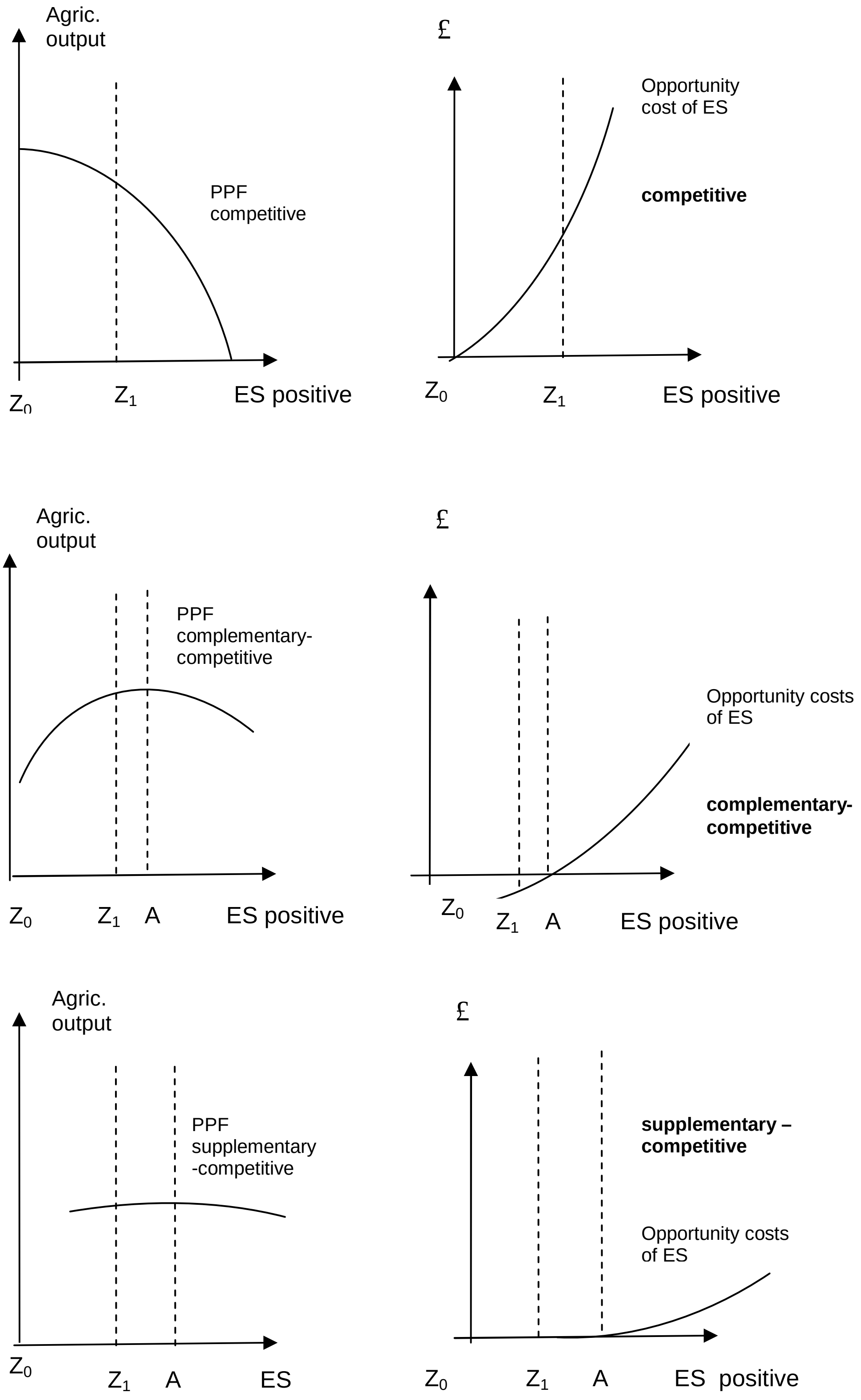


Table 1 — Summary statistics of the data used in the estimation of the transformation function

Variable	Description	Mean	Std. Dev.	Min.	Max.
Y_{AO}	Agricultural output (£)	74910.40	97658.10	1690.06	972295.00
Z_{ESS}	ESS related output (payment in £/farm)	3897.66	4415.31	340.18	29473.10
Z_{HFA}	HFA related output (payment in £/farm)	4250.30	3321.72	89.93	18238.50
Y_{NAO}	Other non-agricultural output (£)[1]	34067.90	30618.40	3548.75	270256.00
X_{LAND}	Land input in ha (utilized agric. area)	174.76	163.71	30.29	1151.08
X_{LAB}	Labor input (hours)	4400.88	3102.17	1182.00	34694.00
X_{CAP}	Total capital input (£)[2]	426364.00	513975.00	281.36	3993350.00
X_{LU}	Lifestock input (in Lifestock Units)	150.24	100.83	16.33	1106.20
X_{MACH}	Machinery input (£)	18737.30	21553.80	2792.03	226385.00
X_{FERT}	Fertilizer input (£)	7765.75	11297.60	0.00	85240.80
X_{CHEM}	Pesticide inputs (£)	1427.36	6906.99	0.00	87189.70
X_{FODVET}	Fodder and veterinary input (£)	19731.50	17794.90	511.14	146162.00
NVZ	% of area under Nitrate Vulnerable Zone program	6.61	24.89	0.00	100.00
LFA	Less Favoured Area Code [3]	3.44	1.41	1.00	7.00
ALT	Altitude code [4]	1.44	0.53	1.00	3.00
AGE	Age of the farm manager	52.42	10.07	25.00	81.00

[1] Calculated as: Total output-YAO-ESS-HFA.

[2] Landlord type capital excl. agric. land (milk quota, buildings, drainage, improvements, woodland)

[3] 1= All land outside LFA; 2 = All land inside SDA (severely disadvantaged area); 3 = All land inside DA; 4 = 50% + in LFA of which 50% + in SDA; 5 = 50% + in LFA of which 50% + in DA; 6 = <50% in LFA of which 50% + in DA; 7=<50% in LFA of which 50% + in DA.

[4] 1 = Most of holding below 300m; 2 = Most of holding at 300m to 600m; 3= Most of holding at 600m or over; 4 = Data not available.

Table 2A — Estimates Fixed-Effects Transformation Function

Parameter	*Estimate*[1]	*Standard error*	*Parameter*	*Estimate*	*Standard error*	*Parameter*	*Estimate*	*Standard error*
a_{0}	182226.564**	48843.919	a_{CAPCAP}	-0.004	0.009	$a_{HFALAND}$	1.601*	2.089
a_{0ESS}	-311.511***	114.533	a_{LULU}	184.411***	34.814	a_{HFALAB}	74.102***	22.563
a_{0HFA}	1797.712***	453.671	$a_{MACHMACH}$	4.541***	1.181	a_{HFACAP}	-27.179***	6.604
a_{0NAO}	113.199***	27.312	$a_{FERTFERT}$	-0.709***	0.286	a_{HFALU}	-0.182***	0.024
a_{0LAND}	-7196.088***	2934.657	$a_{CHEMCHEM}$	16.162***	2.657	$a_{HFAMACH}$	57.773***	23.492
a_{0LABOR}	-176.214	900.007	$a_{FODVETFODVET}$	0.493***	0.071	$a_{HFAFERT}$	-3.712	2.869
a_{0CAP}	6.849***	2.579	b_{TT}	5178.999*	3071.526	$a_{HFACHEM}$	-0.699***	0.128
a_{0LU}	-2657.041**	557.703	a_{ESSHFA}	-4.751*	3.077	$a_{HFAFODVET}$	0.235***	0.039
a_{0MACH}	-270.374*	33.522	a_{ESSNAO}	-1.462*	1.001	$a_{NAOLAND}$	-5.117***	1.946
a_{0FERT}	180.603***	25.153	$a_{ESSLAND}$	16.664	22.754	a_{NAOLAB}	28.930**	12.136
a_{0CHEM}	-161.961***	47.495	a_{ESSLAB}	11.495*	7.138	a_{NAOCAP}	4.977	13.302
$a_{0FODVET}$	-367.333*	211.966	a_{ESSCAP}	-0.321	0.285	a_{NAOLU}	-3.698*	2.314
b_{T}	-48826.227***	19862.861	a_{ESSLU}	119.848***	37.061	$a_{NAOMACH}$	0.106***	0.014
a_{ESSESS}	-1.915**	1.045	$a_{ESSMACH}$	-2.055	2.584	$a_{NAOFERT}$	-55.407**	25.952
a_{HFAHFA}	-6.453***	2.454	$a_{ESSFERT}$	-0.019	1.611	$a_{NAOCHEM}$	3.783**	1.462
a_{NAONAO}	1.361**	0.825	$a_{ESSCHEM}$	0.576***	0.069	$a_{NAOFODVET}$	0.269	0.787
$a_{LANDLAND}$	-186.593***	62.897	$a_{ESSFODVET}$	-7.452***	2.593	$a_{LANDLAB}$	-8.281***	2.072
a_{LABLAB}	-11.959**	6.805	a_{HFANAO}	36.643**	20.087	$a_{LANDCAP}$	1.868*	1.017

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

Table 2A *(Cont.)*

Parameter	***Estimate***[1]	***Standard error***	***Parameter***	***Estimate***	***Standard error***	***Parameter***	***Estimate***	***Standard error***
a_{LANDLU}	-190.119***	73.034	$a_{LUFODVET}$	0.422**	0.221	nitrate vulnerable zone	-3140.623	4444.565
$a_{LANDMACH}$	142.358	46.913	$a_{MACHFERT}$	-0.013	0.121	organic production	-13184.419**	5189.519
$a_{LANDFERT}$	1.248	1.283	$a_{MACHCHEM}$	4.918***	0.657	less favoured area (50-100% in SDA[2])	-95676.066***	24135.419
$a_{LANDCHEM}$	208.702***	26.562	$a_{MACHFODVET}$	-21.641	30.424	less favoured area (50-100% in DA[2])	-96401.285***	24194.983
$a_{LANDFODVET}$	-32.079*	18.209	$a_{FERTCHEM}$	11.414	16.197	altitude (most of holding 300-600m)	-4660.265***	938.958
a_{LABCAP}	-8.891***	1.018	$a_{FERTFODVET}$	217.319***	39.924	altitude (most of holding >600m)	-8024.789***	925.574
a_{LABLU}	11.830	33.520	$a_{CHEMFODVET}$	-13.106***	2.694	age	51.867	101.923
$a_{LABMACH}$	26.849*	13.104	b_{ESST}	2227.778*	1304.847			
$a_{LABFERT}$	-183.965	790.525	b_{HFAT}	-0.232	1.047			
$a_{LABCHEM}$	0.587*	0.322	b_{NAOT}	-6.205**	2.714			
$a_{LABFODVET}$	-25.895***	7.892	b_{LANDT}	-1.012	1.493			
a_{CAPLU}	0.291	0.469	b_{LABT}	92.111***	7.679			
$a_{CAPMACH}$	1.992***	0.235	b_{CAPT}	-2.396*	1.062			
$a_{CAPFERT}$	-13.791*	6.317	b_{LUT}	-1.179*	0.781			
$a_{CAPCHEM}$	14.837***	3.147	b_{MACHT}	9.886*	70.821			
$a_{CAPFODVET}$	108.651	195.812	b_{FERTT}	-6.069***	2.141			
a_{LUMACH}	-0.177	2.545	b_{CHEMT}	283.304*	122.446			
a_{LUFERT}	-0.443	0.178	$b_{FODVETT}$	67.074*	38.358			
a_{LUCHEM}	0.037***	0.008						

Model quality measures and diagnostic test results

R-squared/Adj. R-squared	0.998/0.983	
F[97, 295]	63.59*** (0.0000)	
Log likelihood	-3811.798	
Chi-sq [97]	2521.12*** (0.0000)	
	R-squared	Loglikelihood
Group effects only	0.731	-4814.922
X- variables only	0.979	-4311.201
X –variables and group effects	0.998	-3811.798
Hausman Test Chi-sq [43]	60.89** (0.030)	
Number of Observations	393	

[1] : *,**,*** : significance at 10%- , 5%- , or 1%-level ; [2]: SDA – Severely Disadvantaged Area, DA – Disadvantaged Area.

Table 2B — Estimated 2nd Order Elasticities for Agri-Environmental Outputs (Delta Method at Sample Means)

	ESS		*HFA*	
Output/Input	*est*[1]	*se*	*est*[1]	*Se*
ESS	-0.006***	0.001	-3.03e-04***	2.47e-05
HFA	-3.03e-04***	2.47e-05	-0.003***	0.001
NAO	-3.23e-05***	4.24e-06	7.75e-04***	2.57e-05
Land	0.005***	7.02e-04	4.73e-04***	6.17e-05
Labor	7.06e-05***	4.51e-06	-0.004***	0.001
Capital	-1.99e-06	1.78e-05	-1.63e-04***	3.95e-05
Livestock	0.039**	0.012	-5.81e-04	7.52e-05
Machinery	-6.12e-05	7.71e-05	0.002	0.001
Fertilizer	-9.19e-07***	7.46e-08	-1.65e-04***	1.27e-05
Chemicals	-6.22e-05**	3.67e-05	-7.22e-05	1.32e-04
Fodder & Veterinary	-2.16e-04**	7.53e-05	-6.53e-05***	1.11e-05
Time	0.572	0.361	-5.69e-04	0.002

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

Table 3 — Estimated 1st Order Elasticities (Delta Method at Sample Means)

Output/Input	*Estimatet*[1]	*Standard error*
ESS	-0.169***	0.039
HFA	-0.188***	0.009
NAO	-0.314**	0.159
LAND	0.071***	0.008
LAB	0.382***	0.064
CAP	0.031***	0.011
LU	0.447***	0.091
MACH	0.175***	0.078
FERT	0.063**	0.029
CHEM	0.216***	0.053
FODVET	0.268***	0.114
T	0.113***	0.009
Returns to Scale	1.036***	0.051

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

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

Table 4 — Descriptive Statistics for Direct and Indirect Effects

Effect evaluated	*Mean*	*Std. Dev.*[1]	*Min*	*Max*
dYAO/dX	227.633	377.814	-672.104	2485.297
dYAO/dZESS	0.481	2.332	-2.913	11.609
dYAO/dZHFA	-1.824	8.654	-40.368	107.134
dYAO/dYNAO	-0.2835	0.068	-0.315	0.142
(dYAO/dZESS)(dZESS/dX)	0.061	0.031	0.005	0.184
(dYAO/dZHFA)(dZHFA/dX)	0.060	0.051	0.006	0.368
(dYAO/dZESS)(dZESS/dHFA)= (dYAO/dZHFA)(dZESS/dZESS)	-4.81e-04	4.06e-04	-0.003	-5.01e-05
(dYAO/dYNAO)/(dYNAO/dZHFA)	9.01e-05	7.74e-05	1.11e-05	5.85e-04
(dYAO/dYNAO)/(dYNAO/dZESS)	-6.01e-05	3.75e-05	-2.72e-04	6.03e-06
(dYAO/dYNAO)(dYNAO/dX)	-0.058	0.005	-0.015	-1.72e-04

[1] calculated at individual observations.

Relationship considered:	Agric. output ESS X	Agric. output HFA X	Agric. output ESS HFA	Agric. output, HFA ESS	Agric. output Non Agric. Output, HFA	Agric. output Non Agric. Output ESS	Agric. output Non Agric. Output X
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	**310**	**310**	0	0	121	0	0
Case II	0	0	121	202	0	**202**	**310**
Case III	83	83	**272**	**191**	**272**	191	83
Total Obs.	393	393	393	393	393	393	393

Table 5 — Estimated Cases and number of observations per case for various Product-Product Relationships[a]

[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 (supplementary).
Case III **-** direct effect <= 0 and indirect effect is negative (competitive).