The economics of biodiversity conservation in agricultural transition

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Paper prepared for presentation at the XI*th *congress of the EAAE
(European Association of Agricultural Economists),
'The Future of Rural Europe in the Global Agri-Food System',
Copenhagen, Denmark: August 24-27, 2005

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Abstract

This paper explores the dynamic effects of biodiversity conservation on agricultural production in the context of specialised intensive farming systems that may be in transition towards more sustainable farming. The focus is on the analysis of the dynamic effects of changes in the levels of agrobiodiversity, on technical change and productivity in intensive agricultural systems. A theoretical model is used to derive hypotheses regarding these linkages that are empirically tested using a stochastic production frontier model with data from a panel of UK cereal farms for the period 1989-2000. The results suggest that the increased agrobiodiversity has positively helped to shift the production frontier outwards. This indicates that agricultural transition from more to less intensive agricultural systems can be consistent with non-decreasing output levels and an enhancement of biodiversity in agricultural landscapes.

KEYWORDS: Agrobiodiversity, Intensive Agriculture, Productivity, Technical change.
JEL: Q12, Q16, Q24.

ACKNOWLEDGEMENTS: We are grateful to the Department of Environment, Food and Rural Affairs and the Centre for Ecology and Hydrology for permission to use data from the Farm Business Survey and the Countryside Survey respectively. We would also like to thank Professor Pierre-Richard Agenor, Economic Studies, School of Social Sciences, University of Manchester for helpful comments on an earlier draft of this paper.

1. Introduction

The emphasis in agricultural practice in industrialised countries is on creating the optimum environment for a single target species (the 'crop'). This is pursued by adjusting the environment so that growing conditions for the target species are optimised while those for competing species (e.g. 'weeds' and 'pests') are deliberately worsened. Swift and Anderson (1993) suggest that biodiversity in agro-ecosystems is grouped into three main components (i) the productive biota, such as crops, trees and animals, (ii) the resource biota or organisms that contribute to productivity through for example pollination, biological control and decomposition/nutrient cycling, and (iii) the 'destructive biota' such as weeds, insect pests and microbial pathogens, which farmers aim at reducing. Most of the components in these groups vary depending on the input management and the spatial/temporal structure of the crops. This view of the agro-ecosystem as involving managed competitive relationships between species has dominated modern agricultural practice implying the simplification of the structure of the environment (Altieri, 1999); the co-operative or integrative polycultures and agroforestry systems are now mostly found in less developed countries where low input agriculture generally reflects lack of capital and specific environmental constraints for intensification of production processes. In these cases agriculture provides a clear multifunctional system where the careful management of soil, water, nutrients, and biological resources can be models of agricultural efficiency (Altieri, 1999). By contrast, the competitive vision of agricultural production ignores potentially symbiotic interactions and resource use complementarities between species and is being questioned for not encompassing factors that may significantly contribute to short and long term agro-ecosystem productivity (Mader et al. 2002). The new thrust of measuring the sustainability of intensive agricultural systems is indicative of this.

An alternative view proposes that ecosystem sustainability is more likely related to maintenance of specific ecosystem functions rather than species per se, thus pointing towards the role of functional diversity (Burel et al., 1998).[i] For instance, soil biodiversity maintains the recycling of nutrients and it allows an adequate balance between organic matter, soil organisms and plant diversity, towards a productive and ecologically balanced soil environment (Hendrix et al., 1990). This implies that sustainability is less related to the diversity of biological species than to preserving particular species that support the necessary ecosystem functions (Di Falco and Perrings, 2003). Hence, in any given agro-ecosystem, additional species might reduce agricultural productivity of the main crop through competition (for nutrients, light etc.), or alternatively might increase output by supporting ecosystem functions that help to enhance productivity (e.g. through pollination, soil nutrient enhancement, integrated pest control etc.). Although the time scales of these effects may differ, thus creating a complex picture of the effect of agro-biodiversity on crop output, there is a balance being struck between direct competition between different species including crop species, and the support provided by non-crop species for the growing crop through agro-ecosystem functions.

This paper seeks to identify the effect of biodiversity conservation on agricultural productivity. The focus is on highly intensified agricultural systems, where due to biodiversity simplification, the system requires high levels of chemical and mechanical inputs and continued human intervention that substitute the ecological system's internal regulation function (Swift and Anderson, 1993). Here we emphasise the inherent dynamics of these systems in transition towards long run equilibrium. It is hypothesised, based on recent ecological studies (Bullock et al. 2001, Richards 2001) that in this type of production system, the positive effect of biodiversity conservation and ecosystem function enhancement, outweigh the competitive effect at the margin. The paper presents a bio-economic model that describes the effect of biodiversity on output and distinguishes this effect from that of increased input use and technical progress. In particular the results from the theoretical analysis provide insights about likely responses to specific exogenous changes along the optimal path of the agro-ecological system. Key hypotheses regarding the dynamic effects are constructed around these insights and are tested by applying an output-based distance function model to data from a panel of specialised cereal producers in the UK for the period 1989-2000.

The paper unfolds as follows. The following section develops a stylised bio-economic model to investigate the dynamics of the relationship between biodiversity, technical change, input use and agricultural output. Then, section 3 describes the data and section 4 estimates a dynamic stochastic frontier model to test the predictions obtained in the theoretical model. Finally the last section concludes.

2. A Model of Agro-Biodiversity and Input Intensification

The present model assumes that decisions for a given tract of land are motivated by a concern for ecosystem damage and are based on the maximisation of the discounted present value of utility flows to perpetuity (Pender, 1998; Forster, 1973). A stylised direct utility function can be specified as $U=U[B(t),Y(t)]$, where $Y(t)$ represents the flow of marketable agricultural output at time t, and $B(t)$ stands for biodiversity loss attributable to intensive use of artificial inputs, $X(t)$, which in turn can be buffered by ecosystem conservation investment, $R(t)$. In this sense, total agricultural production is allocated between $Y(t)$ and $R(t)$.

The model reflects a subset of economic decisions that would principally affect land use activities, and the welfare that these activities generate. The problem is to find the optimal trade-off in the allocation of utility yielding services: agricultural supply, $Y(t)$, and the biodiversity stock, $Z(t)$.[ii] It is also assumed that the marginal utilities are as follows: $U_Y > 0, U_{YY} < 0,$ and $U_B < 0, U_{BB} < 0,$ for a strictly concave and linearly separable utility function.

As agricultural processes rely on the integrity of the agro-ecosystem for productivity and sustainability, the modelling of agricultural development over time should consider the relationship between agricultural productivity and biodiversity. Recent ecological studies suggest that the relationship is positive (Bullock et al. 2001, Richards, 2001). Hence, the stock of biodiversity, $Z(t)$, enters into the production function alongside $X(t)$, i.e. $F[X(t),Z(t)]$ represents potential agricultural output and is assumed to exhibit strict concavity with $F_Z > 0, F_{ZZ} < 0$ and $F_X > 0, F_{XX} < 0$, alongside weak essentiality, $F(0) = 0$.

In the present model, biodiversity conveys a somewhat general notion at any of three levels (species, genetic and ecosystem diversity) with each level having a set of sub-components and hence a different interaction with the production process. This implies that the effect of a change in *Z(t)*, on the marginal product of *X(t)*, is likely to be different at each level or sublevel of *Z(t)*. For instance, an increase in insect or micro-organism diversity would increase the marginal product of fertiliser since it enhances soil productivity ($F_{XZ} \geq 0$). Alternatively, an increase in natural vegetation diversity would decrease the marginal product of fertiliser as it increases the competition against the cultivated crops ($F_{XZ} \leq 0$). Similar examples could be stated for other components of biodiversity. Due to this ambiguity, *F[X(t), Z(t)]* is assumed linearly separable in *Z(t)* and *X(t)*. Additionally, a dynamic production function is proposed in the form of *F[X(t),Z(t),A(t)]*, where *A(t)* represents the state of technology as an exogenous shifter of the production possibility frontier that evolves through time, i.e. a simple representation of neutral technical progress .

The biodiversity impact (or loss) function, *B=B[X(t),Z(t)]*, is assumed to depend on the level of agricultural intensification through use of *X(t)*, and on the state of biodiversity, *Z(t)*. The latter effect is included to reflect the notion that the level of biodiversity makes a positive contribution to ecological integrity, in the sense that biodiversity can enhance the ability of the agro-ecosystem to tolerate and overcome the adverse effect of agricultural activities (Swanson 1997, Xu and Mage 2001). It is further assumed that, at the margin biodiversity loss increases (decreases) at an increasing (decreasing) rate due to increases in input intensification (biodiversity stock) i.e. $B_X > 0, B_{XX} > 0$, and $B_Z < 0, B_{ZZ} > 0$, and for simplicity that the biodiversity impact function is linearly separable in *X* and *Z*.

The decision maker has to choose the optimal time paths of the control variables *Y(t)* and *X(t)*, accounting for the evolution of *Z(t)* in the agro-ecosystem. This evolution reflects, biodiversity stock, conservation investments (*R*), and artificial input use. More generally this can be expressed as:

$$\dot{Z} = G[Z(t), X(t), R(t)] \tag{1}$$

and, using a simple linear function, as[iii]:

$$\dot{Z} = \alpha Z + \delta R - \gamma X \tag{1a}$$

where α, δ and γ are all constant parameters. According to equation (1a), *Z* is enhanced proportionally to investment in conservation, *R*, δ being the rate of induced growth[iv], and it is proportionally reduced due to artificial input application. It is worth noting that whilst biodiversity is considered to be natural capital, it is assumed that no depletion in biodiversity occurs as a result of its support to the production process.

Since the optimisation problem is specified with an infinite time horizon, it can be shown that the solution of the first order conditions would lead to a steady state marked as ($\overline{Z}, \overline{Y}, \overline{X}, \overline{\varphi}$) and it is reachable from the initial state condition $Z(0) = Z_0$. That is, there is an implicit terminal state $\lim_{t \to \infty} Z(t) = \overline{Z}(\phi)$ where ϕ is a vector of exogenous parameters and variables including the discount rate, ρ, and technological progress, *A*. The problem is described as:

$$\underset{Y,X,R}{Max}\, W(Y(t), B(t)) = \int_{t=0}^{\infty} e^{-\rho t} u(Y(t), B(t)) dt \tag{2}$$

where $\rho > 0$ is the utility discount rate, subject to (i) the equation of motion for *Z(t)*, (ii) the non-negativity constraints, i.e. $X \geq 0$ and $B \geq 0$, (iii) the initial condition $Z(0) = Z_0$, (iv) the impact function *B(.),* and (v) the environmental conservation investment function (3):

$$R(t) = F[X(t), Z(t)] - Y(t) \tag{3}$$

This yields the current-value Hamiltonian: $H_C = U(Y, B) + \varphi(\alpha Z + \delta F(.) - \delta Y - \gamma X)$ (4)

where φ is the current shadow value of biodiversity. The Maximum Principle for an interior solution shows that:[v]

$$\frac{\partial H_C}{\partial \varphi} = \dot{Z} = \alpha Z + \delta[F(.) - Y] - \gamma X \tag{5a}$$

$$\frac{\partial H_C}{\partial Y} = U_Y - \delta \varphi = 0 \tag{5b}$$

$$\frac{\partial H_C}{\partial X} = U_B B_X + \varphi(\delta F_X - \gamma) = 0 \tag{5c}$$

$$\dot{\varphi} = -U_B B_Z - \varphi(\alpha + \delta F_Z - \rho) = -\frac{\partial H_C}{\partial Z} + \rho \varphi \tag{5d}$$

Equation (5a) restates the state equation, (5b) establishes that the current shadow value of biodiversity (φ) is positive, while (5c) states that *X* should be allocated such that the marginal utility and disutility of artificial input use are balanced. For an interior solution, the bracketed term $(\delta F_X - \gamma)$ is positive as φ is positive and the first term is unambiguously negative. Equation (5d) is the standard non-arbitrage condition which dictates that for an optimal solution, no gain in utility can be achieved by reallocating natural capital in the form of biodiversity from one period to another. This occurs when the current marginal return to *Z(t)* equals its marginal cost.

From (5b-5c) *X* can be defined as an implicit function of *Y* and *Z* with $X_Z > 0$ and $X_Y < 0$, i.e. *X (Y, Z)* is the level of *X* that solves the optimality conditions. In addition, the optimal path for *Y* can be derived from the Maximum Principle by totally differentiating (5b) with respect to time:

$$\dot{Y} = -\frac{U_Y}{U_{YY}}\left[\alpha - \rho + \delta F_Z - (\delta F_X - \gamma)\frac{B_Z}{B_X}\right]$$

which together with the evolution of biodiversity (5a) describes the dynamic system of equations in a (*Z, Y*) space:

$$\dot{Z} = g(Z, Y)$$

$$\dot{Y} = f(Z, Y)$$

Two positively sloped demarcation curves ($\dot{Z} = 0$ and $\dot{Y} = 0$) are drawn, that divide the phase space into four regions, with a different mix of time derivatives for *Y(t)* and *Z(t)* (Figure 1).

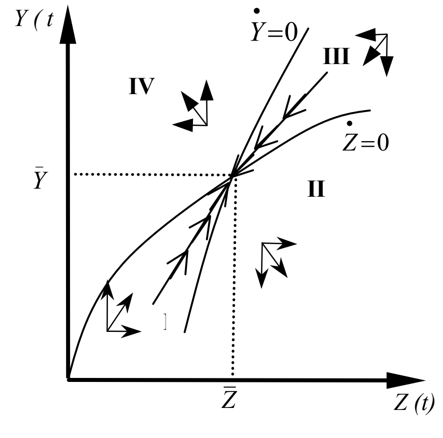

Figure 1: Saddle point equilibrium in the (Z,Y) phase space

The effect on agricultural output of technological change and biodiversity can be investigated using both static and dynamic comparative analyses. The steady state equilibrium for biodiversity and output is given, respectively, by

$$\bar{Z} = -\tfrac{1}{|J_S|}\left[f_Y(\alpha Z + \delta F - \delta Y - \gamma X) + g_Y \frac{U_Y}{U_{YY}}\left(\alpha - \rho + \delta F_Z - [\delta F_X - \gamma]\frac{B_Z}{B_X} \right)\right] \qquad (6a)$$

$$\bar{Y} = -\tfrac{1}{|J_S|}\left[- f_Z(\alpha Z + \delta F - \delta Y - \gamma X) - g_Z \frac{U_Y}{U_{YY}}\left(\alpha - \rho + \delta F_Z - [\delta F_X - \gamma]\frac{B_Z}{B_X} \right)\right] \qquad (6b)$$

(see appendix[vi]). To investigate the effect of an exogenous change in *A* on the steady state, equation (6) can be differentiated with respect to A:

$$\frac{\partial \bar{Z}}{\partial A} = \frac{-\delta F_A f_Y}{|J_S|} > 0 \qquad (7a)$$

$$\frac{\partial \bar{Y}}{\partial A} = \frac{\delta F_A f_Z}{|J_S|} > 0 \qquad (7b)$$

According to the model, an increase in technological progress, leads to higher steady state value of both *Z* and *Y*. More interesting is the comparative dynamic analysis regarding how the state and control variables change along their optimal time paths in response to changes in technological progress (*A*). The optimal time paths, defined by the definite solution of the dynamic system of the model are given as: [vii]

$$\begin{bmatrix} Z(t;Z_0,\phi) \\ Y(t;Z_0,\phi) \end{bmatrix} = \begin{bmatrix} \bar{Z} \\ \bar{Y} \end{bmatrix} + \left[Z_0 - \bar{Z} \right] \begin{bmatrix} 1 \\ k_1 \end{bmatrix} e^{r_1 t} \qquad (8a)$$

where:

$$k_1 = \frac{-\dot{Y}_Z - \left(r_1 - \dot{Z}_Z\right)}{r_1 - \dot{Y}_Y + \dot{Z}_Y} < 0 \qquad (8b)$$

and r_1 is the negative characteristic root (see appendix[v]). From (8a, 8b) the local comparative dynamic effect of *Y* with respect to *A* can be derived:

$$\left. \frac{\partial Y(t;Z_0,\phi)}{\partial A} \right|_{Z_0 = \bar{Z}} = \bar{Y}_A - \bar{Z}_A k_1 e^{r_1 t} > 0 \qquad (9a)$$

Equation (9a) states that optimal marketable crop output increases with an increase in technological progress but at a decreasing rate. This result is restated in the following proposition:

Proposition 1: *The effect of improving technology is to increase marketable output Y(t) along the optimal path at a declining rate until the new steady state equilibrium is reached.*
Proof: As $k_1 < 0$ and $r_1 < 0$, the term $\bar{Z}_A k_1 e^{r_1 t}$ <0 and its absolute value declines as time increases (see appendix[v]).

The impact of biodiversity on marketable output can also be investigated through comparative dynamic analysis. $\left. \frac{\partial Y(t;Z_0,\phi)}{\partial \bar{Z}} \right|_{Z_0 = \bar{Z}} = -k_1 e^{r_1 t} > 0$ (9b)

Equation (9b) yields the following proposition:

Proposition 2: *Along the optimal path, marketable output increases with increases in biodiversity at a decreasing rate until the new steady state equilibrium is reached.*
Proof: In the long run, the term $k_1 e^{r_1 t}$ approaches zero as time goes to infinity since r_1<0 (see appendix[v]).

Taken jointly, these two propositions imply that output can be increased, although at a declining rate, by either improving the state of technology or by enhancing the levels of biodiversity in agricultural landscapes. The policy maker can choose between the two strategies to increase food production in the long run.

3. The Data

The empirical analysis is focused on testing these two propositions using a data set comprising a panel of approximately 230 cereal producers from the East of England, between 1989 and 2000, yielding a total sample size of 2,778 observations.[viii] These data allow the estimation of a dynamic frontier production model that provides an explicit representation of the production surface underlying the theoretical analysis, where it is assumed that farmers have optimally adjusted their production processes and hence are operating on the frontier.

The data set includes information on cereal output, level of input application and some socioeconomic characteristics of the farm households. In addition, a measure of biodiversity is constructed that allows investigation of the relationship between biodiversity and agricultural productivity that was predicted by the theoretical model. The per-hectare variables used in the econometric model are: (i) crop yield**,** (ii) hired and imputed family labour (iii) use of machinery, fertilisers and pesticides, and (iv) the biodiversity index. All the variables on inputs and output are derived from value measures deflated by the relevant Agricultural Price Index (API base year 1990). Summary statistics for these variables appear in Table 1.

Table 1: Summary statistics for variables in the stochastic frontier models for cereal farmers in the East of England

Variable	Mean	St. Dev	Minimum	Maximum
Output (£/ha/API)	874.85	194.49	261.55	5141.61
Biodiversity index	13.63	1.04	9.99	16.22
Fertiliser (£/ha/API)	87.55	32.78	0.68	571.90
Labour (£/ha/API)	163.87	92.56	3.34	1093.45
Machinery (£/ha/API)	208.98	93.51	12.55	1382.01
Pesticide use (£/ha/API)	91.41	27.57	1.99	345.62
Area (ha)	178.58	137.21	7.89	1008.18
Age (years)	50.91	10.52	27	79
Environmental Payments (£/ha/API)	2.77	11.00	0	93.63
Proportion Hired Labour (0-1)	0.44	0.25	0	1

A total of 2788 observations were obtained in an unbalanced panel of approximately 230 different specialist cereal farms over the period 1989-2000.
API: Agricultural Price Index for the relevant inputs (or output) and year.

The key relationships between agricultural activity and biodiversity are based on measures of species diversity from the Countryside Surveys (Haines-Young et al. 2003) and indices of input use and conservation activity on panel farms derived from the UK Farm Business Survey (Defra, 2002a). Parameters of this relationship, initially estimated for the panel as a whole, are applied to the farm level data set to generate a farm level biodiversity index for all farms over the 1989-2000 period.

This index is constructed to take into account biodiversity of the whole agro-ecosystem including non-cropped areas such as field margins, hedge-rows and other semi-natural habitats embedded in the cropping area. This is consistent with a number of ecological studies (e.g. Boatman, 1994; Altieri, 1999) that emphasise the role of these non-cropped areas in enhancing the biodiversity and ecological functioning of arable ecosystems.

The index is based on measures of plant diversity (species richness) for Environmental Zone 1 (EZ1)[ix] in the UK Countryside Survey census since it overlaps closely with the area spanned by the panel of farms. The constructed measure of species richness, based on plant species, exploits the information disaggregated by eight Aggregate Vegetation Classes (AVCs)[x] and a number of Broad Habitats in EZ1. The index is then constructed using the aggregation approach described by Wenum et al. (1999). In addition, since farms often cover more than one habitat type, habitat diversity has also been considered. Additionally, the farm level index controls for landscape feature heterogeneity e.g. hedges, walls and field margins, which typically host diverse vegetation classes. The index (representing Z in the theoretical model) is given by:

$$Z = \sum_j \sum_i a_j n_{ij} S_{ij} \tag{10}$$

where, S_{ij} is the mean species richness of AVC i in Broad Habitat j; n_{ij} stands for the measure of AVC i dominance in Broad Habitat j, i.e. the relative number of plots of AVC_i in BH_j to the total number of plots of all AVCs in BH_j; lastly a_j is the scalar associated with Broad Habitat dominance, i.e. the relative area of BH_j in the Environmental Zone under scrutiny.[xi] The evolution of the biodiversity index at the EZ1 level is calibrated as a non-linear discrete-time aggregate version of equation (1b). This calls for calibrating the influence on biodiversity of a measure of biodiversity conservation, *R,* and a biodiversity-degrading input intensification measure, *X:*

$$Z_{t+1} - Z_t = \alpha \ln Z_t - \gamma \ln X_t + \delta R_t, \tag{11}$$

where *R* is a categorical variable that represents the introduction of agri-environmental schemes following the CAP reform[xii] in 1992, and *X* is based on national average pesticide use. Using OLS, the calibrated parameter values of equation (11) (standard deviations in brackets) are as follows: α=0.32 (0.18), γ=2.24 (0.88), δ=0.31 (0.41). Using this parameterisation of the state equation at EZ1 level, an iterative process is used to estimate the value of *Z(t)* for each farm in the panel, given farm-level observations for *R, X,* and a starting value for *Z.* The yearly average farm-specific index is presented in Figure 2 together with crop yield and variable input use in index form (1990 = 100).

It can be observed that cereal yields increase substantially over the period, with a dip below trend in 1995 and a substantial recovery towards the end of the period. The biodiversity index fluctuates slightly as a consequence of the evolution of pesticide and the incorporation in 1992 of the new agri-environmental schemes for biodiversity conservation. While variable inputs fluctuate throughout the period, agricultural prices remain relatively stable until 1996, showing a significant downward trend thereafter.

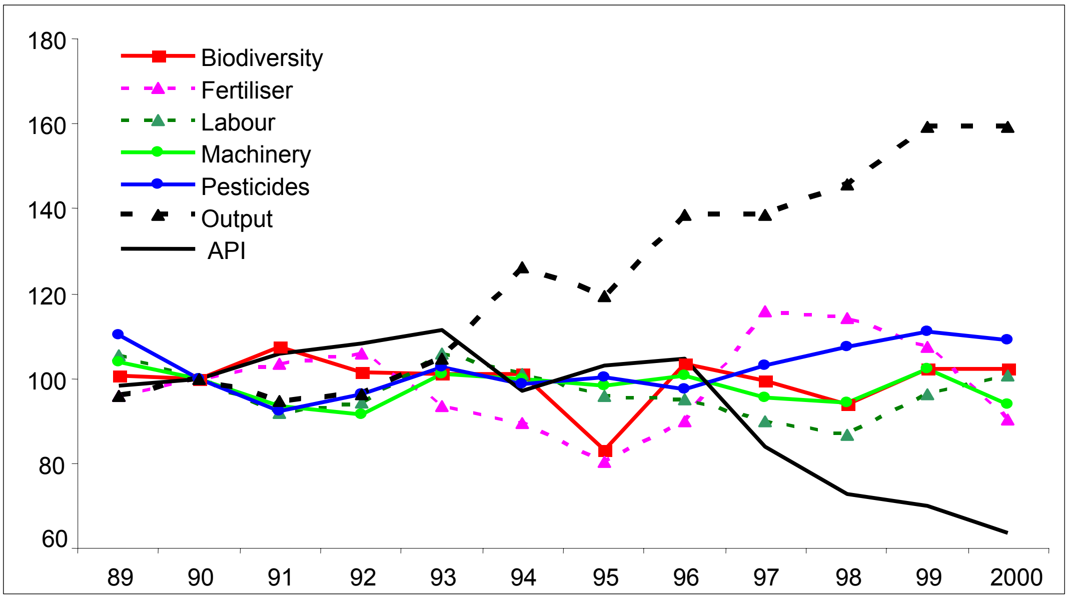

Figure 2: Average indexed (1990=100) values for all inputs, 1989-2000

Note: The baseline data values for 1990 are as follows: Biodiversity = 13.53 (index); Fertilizer = £88/ha; labour=£169/ha; Machinery = £213/ha; Pesticide = £89/ha; Yield = £737/ha. API: Agricultural Price Index (£)

4. The Empirical Model

In order to test the key propositions from the theoretical model, a reduced form stochastic production frontier (SFP) model is defined for arable crop production on cereal farms in the East of England.[xiii] The frontier represents best practice among farmers in the sample and deviations are attributed to the effects of variation in farmer efficiency. In this way, this model allows us to better identify the stylised relationships investigated in the theoretical model using the data generated by real agricultural production processes. Thus we can investigate the key relationships along the production frontier as it evolves over time, since the frontier provides a closer approximation to the "optimal path" (the focus of propositions 1 and 2) than a more traditional econometric specification.

The SFP model fitted to the twelve years, t=1,2,…,T, and farm-specific data, i, takes the following form:

$$Y_{it} = \beta_0 + \sum_k \beta_k X_{kit} + V_{it} - U_{it} \qquad (12)$$

where[xiv]:

Y_{it}: natural log of crop yield of farm i at time t (x £100 per ha/API);
X_1: natural log of biodiversity index;
X_2: natural log of fertiliser use (x£100 per ha/API);
X_3: natural log of labour use (x£100 per ha/API);
X_4: natural log of machinery use (x£100 per ha/API);
X_5: natural log of pesticide use (x£100 per ha/API);
X_6: year of observation where X_6 = 1, 2,…,12.

The β_k k=1..6, are the associated frontier parameters to be estimated and the V_{it}s are assumed to be independently and identically $N(0,\sigma_v^2)$ distributed random errors, independent of the non-negative random error term, U_{it}, associated with technical inefficiency in production.[xv] Three different frontier models are considered based on different specifications for U_{it}s. The Cobb-Douglas SFP function (12) is estimated, given three different specifications of the technical inefficiency effects defined by equations (12a), (12b) and (12c). Several versions of each of these three models were estimated (using the FRONTIER4 software; Batese and Coelli, 1992) to test various hypotheses using the generalized likelihood ratio statistics (Table 3).

Model 1 is a time-varying inefficiency model, as described by Battese and Coelli (1992), in which the inefficiency effects are defined as:

$$U_{it} = \{\exp[-\eta(t-T)]\}U_i \qquad (12a)$$

where η is an unknown parameter to be estimated, and U_i =1,2,…,N, are independent and identically distributed non-negative random variables obtained by the truncation, at zero, of a the $N(\mu,\sigma_u^2)$ distribution. Equation (12a) specifies the technical inefficiency effects of the sample farms in previous periods of the panel as a deterministic exponential function of the inefficiency effects for the corresponding farms in the last period of the panel, T (Battese and Coelli, 1992). The parameter estimates for model 1 are given in table 4.

Model 2 corresponds to an inefficiency effects neutral stochastic frontier model (Battese and Coelli, 1995), the inefficiency effects being defined as:

$$U_{it} = \delta_0 + \sum_j \delta_j Z_{jit} + W_{it} \qquad (12b)$$

where the δ_j j=1…6 coefficients are associated with the effects of the following inefficiency effects covariates:

Z_1 : Natural log of farmer's age (years);
Z_2 : Natural log of income obtained through 'environmental payments';
Z_3 : Dummy variable, 1 if the farm participates in any agri-environmental scheme introduced in 1992, 0 otherwise;
Z_4 : Proportion of hired labour used in the farm;
Z_5 : Dummy variable, 1 if use of hired labour hours, 0 otherwise;
Z_6 : Year of observation, $t=1,2...,12$.

Lastly, the $W_{it}s$ are unobservable non-negative random variables assumed independent and identically distributed, obtained by the truncation at zero of a the $N(0,\sigma_u^2)$ distribution.

Model 3 is a non-neutral stochastic frontier model, in which the inefficiency effects are defined as:

$$U_{it} = \delta_0 + \sum_j \delta_j Z_{jit} + \sum_j \sum_k \delta_{jk} X_{kit} Z_{jit} + W_{it} \qquad (12c)$$

This model is an extended version of model 2, with interactions between farm-specific variables (Zs) and the variable input variables (Xs) in the stochastic frontier. It should be noted that model 2 and 3 are not a generalisation of model 1. Table 2 shows the results of various hypothesis tests regarding the specification of the three models.

Given the specification of model 1, the null hypothesis that deviations from the frontier are insignificant (technical inefficiency is absent), i.e. H_0: $\gamma = 0$, is strongly rejected by the data, where parameter γ is defined as $\gamma \equiv \sigma^2/(\sigma_v^2 + \sigma^2)$. The null hypotheses of a time stationary frontier (no technical change), H_0: β_6=0, and that the deviations (technical inefficiency effects) are time invariant, H_0: $\eta = 0$,

Table 2: Generalized Likelihood-Ratio Tests for SPF models for Cereal Farmers in the East of England (1989-2000)

Null Hypothesis	Log likelihood	LR statistic	CV (5%)
Model 1	1604.34		
H_0: $\gamma = 0$	1007.31	1194.07	7.05*
$H_0 : \beta_6 = 0$	1311.12	586.44	3.84
$H_0 = \eta = 0$	1586.76	35.17	3.84
$H_0 = \mu = 0$	1602.66	3.36	3.84
Model 2	1261.79		
H_0: $\gamma = \delta_0 = \delta_j = 0$	1007.31	508.97	16.27*
$H_0 = \beta_1 = 0$	1257.26	9.07	3.84
$H_0 = \beta_6 = 0$	1084.93	353.72	3.84
$H_0 : \delta_1 = ... = \delta_6 = 0$	1159.36	204.87	12.59
Model 3	1361.13		
H_0: $\gamma = \delta_0 = \delta_j = \delta_{jk} = 0$	1007.31	707.65	55.19*
$H_0 = \beta_1 = 0, \delta_{1j} = 0, j = 1,....,6$	1352.69	16.87	14.07
$H_0 : \beta_6 = 0, \delta_{6j} = 0, j = 1,....,6$	1177.02	368.23	14.07
$H_0 : \delta_{jk} = 0, k, j = 1,.....6$	1261.79	198.67	43.77
$H_0 : \delta_{6k} = \delta_{k6} = 0, k = 1,...,6$	1318.76	84.73	11.07
$H_0 : \delta_{6j} = \delta_{6j} = 0, j = 1,...,6$	1313.58	95.09	11.07
$H_0 : \delta_{3k} = \delta_{4k} = 0, k = 1,...,6$	1341.35	39.56	19.92

*This CV (critical value) is obtained from Kodde and Palm (1986). LR: Likelihood Ratio.

are also rejected at any meaningful significance level. In addition, the half-normal distribution is not an inadequate representation of the distribution of the technical inefficiency effects, i.e. H_0: $\mu = 0$ cannot be rejected at the 5% level of significance. These results thus favor the representation of Model 1 with a half normal distribution and time-varying farm inefficiency effects. It can be noted that technical inefficiency decreases over time, i.e. $\eta > 0$ (Table 3).

Given Model 2, the null hypothesis that inefficiency is not present, H_0: $\gamma = \delta_0 = \delta_j = \delta_{jk} = 0$, and that there is no technical change, H_0: $\beta_6 = 0$, can both be rejected. Furthermore, the hypothesis that the neutral specification of the model outperforms Model 3 is also rejected by the data, i.e. H_0:δ_{jk}=0. Similarly, the null for no year interaction with the explanatory variables in the inefficiency sub-model, H_0: $\delta_{6k} = 0$ is also rejected by the data. Parameter estimates for models 1 and 3 are shown in Table 3.

Table 3: MLE parameter estimates of the generalized C-D SPF models 1 and 3

		Model 1		Model 3	
		Coefficient	T-ratio	Coefficient	T-ratio
Constant	β_0	1.81	23.49	1.69	12.33
X1: Biodiversity	β_1	0.07	2.58	0.13	2.58
X2: Fertilizer	β_2	0.04	5.17	0.05	4.03
X3: Labour	β_3	0.02	2.91	0.01	2.91
X4: Machinery	β_4	0.08	8.56	0.05	4.16
X5: Pesticides	β_5	0.14	14.47	0.14	11.63
X6: Time	β_6	0.05	35.91	0.04	31.67
Inefficiency model					
Constant	δ_0			-0.60	-3.62
Z1: Age	δ_1			-0.05	-2.47
Z2: Environmental pay	δ_2			0.10	3.50
Z3: D1	δ_3			-0.68	-0.73
Z4: Hired labour	δ_4			0.38	0.42
Z5: D2	δ_5			0.71	0.77
Z6: Time	δ_6			0.29	2.16
X1.Z1	δ_{11}			0.02	2.78
X1.Z2	δ_{12}			-0.04	-3.50
X1.Z3	δ_{13}			0.42	1.18
X1.Z4	δ_{14}			-0.04	-0.11
X1.Z5	δ_{15}			-0.24	-0.70
X1.Z6	δ_{16}			-0.08	-1.66
X2.Z1	δ_{21}			0.01	4.74
X2.Z2	δ_{22}			-0.01	-2.83
X2.Z3	δ_{23}			0.75	5.16
X2.Z4	δ_{24}			0.22	2.41
X2.Z5	δ_{25}			-0.20	-2.62
X2.Z6	δ_{26}			-0.04	-6.27
X3.Z1	δ_{31}			0.00	3.09
X3.Z2	δ_{32}			0.00	1.81
X3.Z3	δ_{33}			-0.19	-2.43
X3.Z4	δ_{34}			-0.19	-3.33
X3.Z5	δ_{35}			-0.05	-1.29
X3.Z6	δ_{36}			0.02	4.02
X4.Z1	δ_{41}			0.00	1.29
X4.Z2	δ_{42}			-0.01	-2.93
X4.Z3	δ_{43}			0.11	0.92
X4.Z4	δ_{44}			-0.46	-5.14
X4.Z5	δ_{45}			0.24	3.76
X4.Z6	δ_{46}			0.00	-0.50
X5.Z1	δ_{51}			0.01	5.45
X5.Z2	δ_{52}			0.00	0.79
X5.Z3	δ_{53}			0.10	0.92
X5.Z4	δ_{54}			-0.05	-0.58
X5.Z5	δ_{55}			-0.38	-5.81
X5.Z6	δ_{56}			-0.05	-6.74
X6.Z1	δ_{61}			0.00	1.63

X6.Z2	δ_{62}			0.00	2.10
X6.Z3	δ_{63}			-0.02	-1.59
X6.Z4	δ_{64}			-0.05	-5.30
X6.Z5	δ_{65}			-0.06	-4.86
X6.Z6	δ_{66}			-0.01	-13.34
Variance Parameters					
σ^2		0.05	11.10	0.08	17.05
γ		0.73	28.35	0.86	63.98
η		0.04	6.00		
Log-likelihood		1586.76		1361.13	

Note: D1: Dummy variable for environmental payments received (1 if received, 0 otherwise); D2 dummy variable for hired labour (1, if positive expenditures in hired labour, 0 otherwise)

The elasticity of output with respect to kth input variable for the non-neutral stochastic frontier production function is given by Battese and Broca (1997):

$$\frac{\partial \ln E(Y_{it})}{\partial X_k} = \frac{\partial \beta X}{\partial X_k} - C_{it}\left(\frac{\partial \mu_{it}}{\partial X_k}\right) \tag{13}$$

where

$$\mu_{it} = \delta_0 + \sum_j \delta_j Z_{jit} + \sum_j \sum_k \delta_{jk} X_{kit} Z_{jit} \tag{13a}$$

$$C_{it} = 1 - \frac{1}{\sigma}\left\{\frac{\phi(\frac{\mu_{it}}{\sigma} - \sigma)}{\varphi(\frac{\mu_{it}}{\sigma} - \sigma)} - \frac{\phi(\frac{\mu_{it}}{\sigma})}{\varphi(\frac{\mu_{it}}{\sigma})}\right\}_{it} \tag{13b}$$

and ϕ and φ represent the density and distribution functions of the standard normal random variable, respectively.

The elasticity of mean output with respect to the *k*th input variable in (13) has two components. One is the elasticity of *frontier output* with respect to the kth input, $\frac{\partial \beta X}{\partial X_k}$, given by the estimated β_ks. The other component is the elasticity of measured *technical efficiency* with respect to the kth input, i.e. $\left[-C_{it}\left(\frac{\partial \mu_{it}}{\partial X_k}\right)\right]$. The mean output, frontier and efficiency elasticities for each of the variable inputs averaged throughout the 1989-2000 period, and the yearly mean output elasticities for each of the inputs, are presented in Tables 4 and 5, respectively. It can be observed that for the whole period, biodiversity is positively affecting mean output levels even though greater biodiversity appears to have negatively affected efficiency in the sector. This has also occurred with the application of fertilisers and more dramatically with the use of farm labour. Regarding the latter, the negative effect on efficiency seems to outweigh the positive effect on the frontier, implying an excessive use of labour in cereal farming. By contrast, the use of machinery and pesticides show a relatively large mean output elasticity due to their positive effect both on the frontier and on technical efficiency. A more detailed scrutiny of elasticity values for each of the years, shows that all inputs, except for labour, have increased their relative impact on mean output levels, and this has influenced a systematic increase in the returns to scale, from 0.11 to 0.88. This indicates that there were decreasing returns to scale in crop output, i.e. increasing the output by 1% would require a more than a 1% increase in the use of inputs (Table 5).

The estimated coefficients and equation (13) allow a test of the validity of the proposition arrived at through the bio-economic model. Model 3 allows the investigation of productivity growth by obtaining estimates of the time derivative of the mean crop output. The estimated time coefficient is significantly different from zero, and points towards technical progress regarding frontier crop output of about 5% per annum.

Table 4: Average crop output elasticities with respect to all the inputs in model 3 (1989-2000)

Variable	Frontier output	Technical efficiency	Mean output
Biodiversity	0.13	-0.10	0.04
Fertiliser	0.05	-0.02	0.03
Labour	0.01	-0.05	-0.03
Machinery	0.05	0.00	0.05
Pesticides	0.14	0.14	0.28
Time	0.04	0.09	0.13

Table 5: Elasticities of mean crop output/ha with respect to all inputs for each year (1989-2000)

Year	Biodiversity	Fertiliser	Labour	Machinery	Pesticides	Productivity growth
1989	-0.18	-0.06	0.02	0.06	0.22	0.05
1990	-0.12	-0.03	0.01	0.05	0.23	0.07
1991	-0.09	-0.01	0.00	0.05	0.26	0.09
1992	-0.08	0.00	-0.01	0.05	0.28	0.11
1993	-0.03	0.01	-0.02	0.05	0.29	0.12
1994	0.01	0.02	-0.03	0.05	0.25	0.12
1995	0.01	0.03	-0.04	0.05	0.29	0.14
1996	0.05	0.04	-0.04	0.04	0.27	0.14
1997	0.14	0.06	-0.05	0.05	0.30	0.16
1998	0.16	0.06	-0.06	0.05	0.30	0.17
1999	0.21	0.07	-0.07	0.06	0.30	0.17
2000	0.26	0.07	-0.07	0.06	0.31	0.19
89-00	0.04	0.03	-0.03	0.05	0.28	0.13

The rate of productivity growth over the period under scrutiny is similarly decomposed into two components associated with technical change (or technical progress) in the frontier and technical efficiency change (Battese et al. 2000). This decomposition of the rate of change of mean crop output with respect to time is given by

$$\frac{\partial \ln E(Y)}{\partial t} = \frac{\partial X\beta}{\partial t} - C\left(\frac{\partial \mu}{\partial t}\right) \qquad (14)$$

where the first and second terms in the right-hand-side of (14) represents the impact of exogenous technical change and the change in technical efficiency levels, respectively. These values over the 12 years are plotted in Figure 3. This indicates that there has been technical progress in frontier output. The rate of technical change along the frontier is positive (about 3.7% per year), and it has been non-declining, i.e. starting at technical progress of 0.8% in 1989, the sector continued to have technical progress, reaching 5.7% in 2000. Hence the data supports proposition 1. [xvi]

The dynamic effect of biodiversity on frontier output can also be investigated. The results as depicted in Figure 4 are consistent with the prediction summarised by Proposition 2, i.e. there is a positive, although declining impact of biodiversity on frontier output. The elasticities of frontier crop output with respect to biodiversity are positive and have tended to decrease at a rate of 0.06% per annum, i.e. from 0.18 in 1989 to 0.11 in 2000 (Figure 4). In addition, the effect of biodiversity on technical efficiency has been different before and after 1996. The negative elasticity of technical efficiency with respect to biodiversity between 1989 to 1996 declined by an average of 4% per annum. After this year, the elasticity of efficiency with respect to biodiversity is positive reaching 0.15 in 2000. The net effect of biodiversity through the impacts on both frontier output and technical

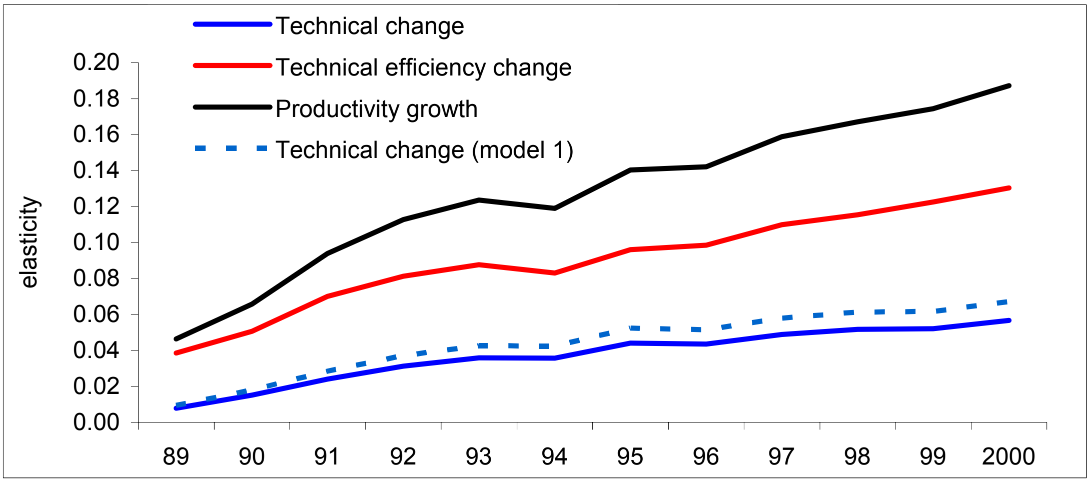

Figure 3: Technical change and productivity growth (1989-2000)

efficiency indicates that while until 1993, the year after broad environmental payments were introduced in the farming sector, higher biodiversity was associated with declining mean yields (average elasticity of -0.1). After the incorporation of the environmental payments to conserve biodiversity, the trend in mean output has reversed with an elasticity in 2000 of 0.26. This indicates that agro-biodiversity conservation schemes have not undermined the productive performance of the cereal sector.

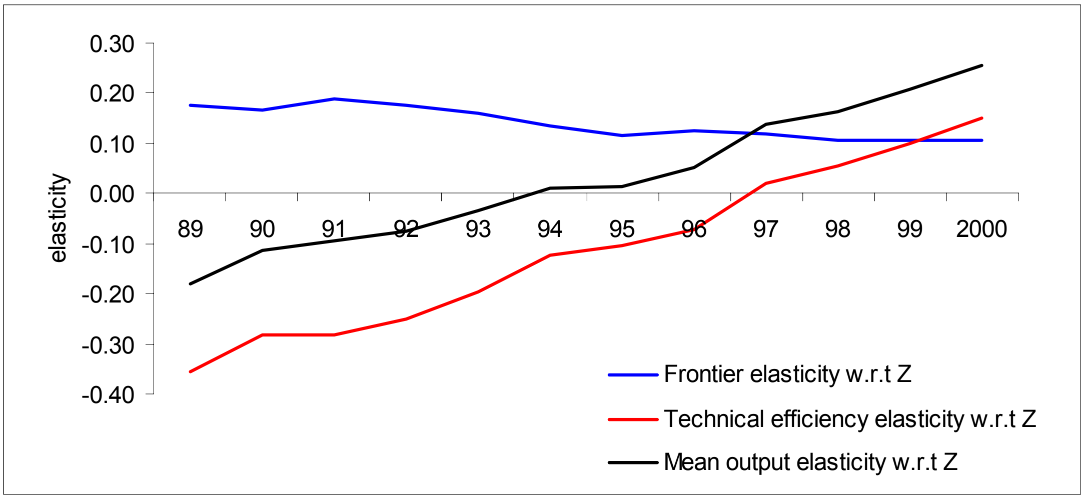

Figure 4: Change in elasticity of output with respect to Biodiversity (1989-2000)

5. Conclusions

A distinguishing characteristic of modern agricultural landscapes is the increasing size and homogeneity of crop monocultures. While the concern for the potential negative environmental effects of monocultures are well established, relatively less attention is being paid to the economic effects of agrobiodiversity loss. While increasing attention is being paid to the potential yield variability and risk towards monocultures (Di Falco and Perrings, 2003), its effects on productivity have not yet been analysed. While ecologists agree that increased intensification is a driver of agro-biodiversity loss, the feedback effects on productivity are less well understood. On the one hand increasing the number of species in a farm may reduce productivity levels of the main crop in the short run through greater competition for abiotic (e.g. light) and biotic resources (e.g. soil nutrients). On the other hand, biodiversity, by providing ecological services (e.g. through pollination, soil nutrient enhancement, and integrated pest control) can increase agricultural output in the longer run, This paper has explored one key link between conservation of agrobiodiversity and crop productivity in the context of specialised intensive farming systems. Departing from agroecological models, a behavioural farm-household model is used to set out the hypothesis that biodiversity can support increased productivity in the longer run, by outward shifts in the output frontier. The empirical analysis to test this hypothesis is based on an output distance function approach using data from cereal farms in England for the period 1989-2000.

The econometric analysis cannot reject our hypothesis. This has important implications for the design of agri-environmental policy as it suggests that the introduction of agrobiodiversity conservation policies in semi-natural habitats can represents a win-win scenario. That is, biodiversity in agricultural landscapes can be enhanced without negatively affecting agricultural productivity in already intensified agricultural sectors. Moreover, it is suggested that not only technical change, but agrobiodiversity conservation in already arable systems can have a positive effect on frontier output levels. In the UK context, from which the data is used, our results complements McInerney et al's (2000) important findings that the additional conservation investment induced by the agri-environmental policy system, as applied in the UK, can generate additional efficiency benefits for farmers and society at large through supporting agriculture's multifunctional nature.

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Notes:

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[i] In agricultural systems, biodiversity performs ecosystem services beyond production of food such as recycling of nutrients, control of local microclimate, regulation of local hydrological processes, regulation of the abundance of undesirable organisms, and detoxification of noxious chemicals (Altieri 1999). However, these valuable ecological functions are not the focus of this paper.

[ii] Note that *Z(t)* refers to the level (*stock*) of biodiversity in time *t*, while *B(t)* refers to biodiversity 'loss' (a *flow* variable).

[iii] This can be interpreted as an extended logistic function, $\dot{Z} = \alpha Z(1 - Z/K) + \delta R - \gamma X$ where $\alpha > 0$ reflects the natural rate of growth of *Z*, and *K* stands for the agro-ecosystem's maximum potential diversity. On intensified agricultural systems with low levels of *Z* relative to its potential maximum, the term *Z/K* is negligible. The linear expression emerges as a simplification.

[iv] The parameter δ also can be interpreted as the marginal degradation in *Z(t)* caused by increase in *Y(t)* i.e. the opportunity cost of *R(t)*.

[v] See Omer et al. (2003) to verify that the current value Hamiltonian is maximised.

[vi] Appendices are available from the authors on request.

[vii] The derivation of the optimal time paths of the system and the comparative dynamics are shown in the appendix.

[viii] The data has been obtained through the annual Farm Business Survey (FBS) undertaken by the Department of Environment, Food and Rural Affairs of the UK (Defra, 2002a). Further, the UK Countryside Surveys undertaken in 1978, 1990 and 1998 have been used to construct the farm level biodiversity index. See Haines-Young et al. (2003) for a summary of the reports.

[ix] In the UK Countryside Survey, Environmental Zones are aggregations of land classes chosen to reflect major environmental variation. Environmental Zone 1 covers major parts of the eastern lowland counties of England.

[x] The Countryside Vegetation System (CVS) describes eight aggregate vegetation types. Data on area of broad habitats is taken from CS2000 (Haines-Young et al., 2003).

[xi] Besides the 1978, 1990 and 1998 periods for which the data from the major ecological surveys are available, two additional observations, for 1997 and 1999, have been constructed from the national estimates on each AVC published as part of CS2000 results adjusted for EZ1. The data for 1978 is not presented by BH, so the BH breakdown from 1990 is used as a proxy for 1978 by merging the two data sets at plot level and then using only those plots for 1978 which are repeated in 1990 to construct the 1978 index.

[xii] The dummy values are zero for periods before 1993 and one for and after 1993.

[xiii] According to the theoretical specification above, total agricultural production is seen as being partitioned between marketable agricultural output, *Y(t),* and conservation investment, *R(t)*.

[xiv] X_1 represents the variable Z in the theoretical model; X_2 to X_5 provide a vector representation of X; X_6 corresponds to A.

This can be represented as follows: Y(t)=*F[*X(t),Z(t)]-R(t)=*h[*X(t),Z(t),R(t)], where *h* is a reduced form function. This full version of the production relationship differs from the simplified version described below that excludes any measure of *R(t)*. Estimates of the full version were derived using agri-environmental payments to farmers as

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a proxy for conservation investment, *R(t)*. However, *R(t)* proves to be statistically not significant at any meaningful level and hence is deleted from the Maximum Likelihood frontier regression. *R(t)* appears as a covariate in the technical inefficiency effects regression.

[xv] A trans-log model was also tried but the interaction terms created significant multicolinearity.

[xvi] In addition the technical efficiency change has been positive throughout the period, and may reflect the turnover of farms during the 1990s' where smaller less efficient farms have been leaving the sector and larger, more efficient ones are increasing in scale. Data for 1997-2002 show average cereals area per farm increasing by around 14% from 48 to 55 hectares (Defra 2003).