Economics and Biodiversity in Intensively Managed Agro-ecosystems

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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. 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). Because it ignores potentially symbiotic interactions and resource use complementarities between species this competitive vision of agricultural production 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 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] 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, and the support provided by non-crop species for the growing crop through agro-ecosystem functions.

This paper investigates 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 as they evolve 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, outweighs 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 adjustment 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.

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. The final section concludes.

2. A Model of Agro-Biodiversity and Input Intensification

The 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 is 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)*. 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.

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)*. Recent ecological studies suggest a positive relationship between agricultural productivity and biodiversity (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 this model, biodiversity encompasses a wide range of species and supports a range of ecological services. This implies that the effect of a change in *Z(t)*, on the marginal product of *X(t)*, depends on the particular species or services affected. 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 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[ii]:

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

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, 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.

The optimisation 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:

$$H_C = U(Y, B) + \varphi(\alpha Z + \delta F(.) - \delta Y - \gamma X) \tag{4}$$

where φ is the current shadow value of biodiversity. The properties of the optimal trajectory can be deduced after applying the Maximum Principle, and a subset of these properties are illustrated by the phase diagram in Figure 1[iii]. The diagram shows that this simple model generates a single saddle-point solution with two convergent isosectors (labelled I and III) in the (Y, Z) plane. In the context of the current analyses attention is focused on low-biodiversity intensive ago-ecosystems notionally represented by points in isosector I.

In this context the effect on agricultural output of technological change and biodiversity can be investigated using both static and dynamic comparative analyses. Thus it is possible to show that an increase in technological progress leads to higher steady state value of both Z and Y. More interestingly it can also be shown that the impact of improving technology is to increase marketable output (Y_t) along the optimal path at a non-declining rate until the new steady state equilibrium is reached. Furthermore, it can be shown that marketable output along the optimal path increases with increases in biodiversity (but at a declining rate) until the new steady state equilibrium is reached.

These two hypotheses are the subject of empirical testing in the remainder of the paper. Taken jointly, they imply that output can be increased, 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 230 cereal producers from the East of England, between 1989 and 2000, yielding a total sample size of 2,778 observations. These data, taken from the UKs Farm Business Survey (Defra, 2002), allow the estimation of a dynamic production frontier model that provides an explicit representation of the production surface underlying the theoretical analysis, where it is assumed that farmers are optimally adjusting their production processes so that they are operating along the frontier.

The data set includes information on cereal output, level of input application and 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:

The key relationship between agricultural activity and biodiversity is based on a measure 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, 2002). 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[iv].

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 use and the introduction 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:

4. The Empirical Model

In order to test the key propositions from the theoretical model, a reduced form stochastic frontier production (SFP) model is defined for arable crop production on cereal farms in the East of England. 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” than a more traditional econometric specification.

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

$$Y_{it} = \beta_0 + \sum_k \beta_k X_{kit} + V_{it} - U_{it} \tag{5}$$

where[v]:

Y_{it}: natural log of crop output per hectare of farm i at time t;

X_1: natural log of biodiversity index;

X_2: natural log of fertiliser use per hectare;

X_3: natural log of labour use per hectare;

X_4: natural log of machinery use per hectare;

X_5: natural log of pesticide use per hectare;

X_6: year of observation where $X_6 = 1, 2,\ldots,12$.

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.[vi]

Three different frontier models were considered based on different specifications for U_{it}s. The Cobb-Douglas SFP function (5) is estimated, given three different specifications of the technical inefficiency effects. 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[vii].

The remaining analysis is based on a non-neutral stochastic frontier model, in which the inefficiency effects are defined as:

$$U_{it} = \delta_0 + \sum_j \delta_j Z_{jit} + \sum_j \sum_k \delta_{jk} X_{kit} Z_{jit} + W_{it} \tag{5a}$$

This specification includes interactions between farm-specific variables (*Z*s) and the variable input variables (*X*s) in the stochastic frontier. Parameter estimates for this model are shown in Table 2.

Table 2:

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) as:

$$\frac{\partial \ln E(Y_{it})}{\partial X_k} = \frac{\partial \beta X}{\partial X_k} - C_{it}\left(\frac{\partial \mu_{it}}{\partial X_k}\right) \tag{6}$$

where
$$\mu_{it} = \delta_0 + \sum_j \delta_j Z_{jit} + \sum_j \sum_k \delta_{jk} X_{kit} Z_{jit} \tag{6a}$$

$$C_{it} = 1 - \frac{1}{\sigma}\left\{ \frac{\phi(\frac{\mu_{it}}{\sigma} - \sigma)}{\varphi(\frac{\mu_{it}}{\sigma} - \sigma)} - \frac{\phi(\frac{\mu_{it}}{\sigma})}{\varphi(\frac{\mu_{it}}{\sigma})} \right\}_{it} \tag{6b}$$

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 (6) 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, are presented in Table 3. 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.

The estimated coefficients and equation (6) allow a test of the validity of the proposition arrived at through the bio-economic model. Productivity growth can be investigated 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 3:

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

$$\frac{\partial \ln E(Y)}{\partial t} = \frac{\partial X\beta}{\partial t} - C\left(\frac{\partial \mu}{\partial t}\right) \qquad (7)$$

where the first and second terms in the right-hand-side of (7) 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 and it has been non-declining. Hence the data supports the first hypothesis.

Figure 3:

The dynamic effect of biodiversity on frontier output can also be investigated. The results as depicted in Figure 4 are consistent with the prediction (the second hypotheses) that 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 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:

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. Increasing attention is being paid to the potential yield variability and risk towards monocultures (Di Falco and Perrings, 2003), but 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 can represent 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 arable systems can have a positive effect on frontier output levels. In the UK context, from which the data is used, our results complement 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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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.

Table 2: MLE parameter estimates of the SPF model

		Coefficient	T-ratio
Constant	β_0	1.69	12.33
X1: Biodiversity	β_1	0.13	2.58
X2: Fertilizer	β_2	0.05	4.03
X3: Labour	β_3	0.01	2.91
X4: Machinery	β_4	0.05	4.16
X5: Pesticides	β_5	0.14	11.63
X6: Time	β_6	0.04	31.67
Inefficiency model			
Constant	δ_0	-0.60	-3.62
Z1: Age	δ_1	-0.05	-2.47
Z2:Environ. 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
…	..	…	…
36 interaction terms 24 of which are significant at 10 per cent level	δ_{12} to δ_{65}	-0.38 thru 0.00 to 0.75	-13.34 to 5.45
…	..	…	…
X6.Z6	δ_{66}	-0.01	-13.34
Variance Parameters			
σ^2		0.08	17.05
γ		0.86	63.98
Log-likelihood		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)

Table 3: Average crop output elasticities with respect to all inputs (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

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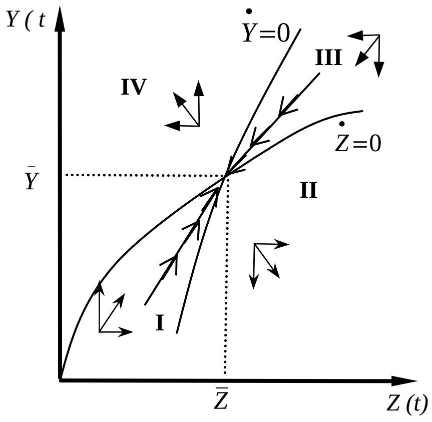

Figure 1: Saddle point equilibrium in the (Z,Y) phase space

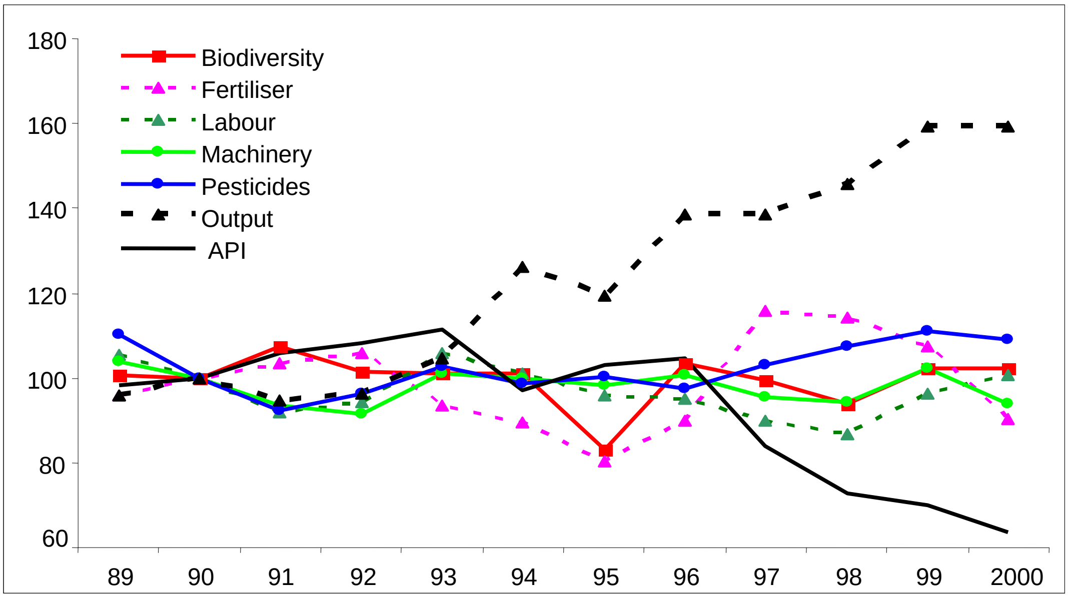

Figure 2: Average indexed (1990=100) values for all inputs, 1989-2000

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 (£)

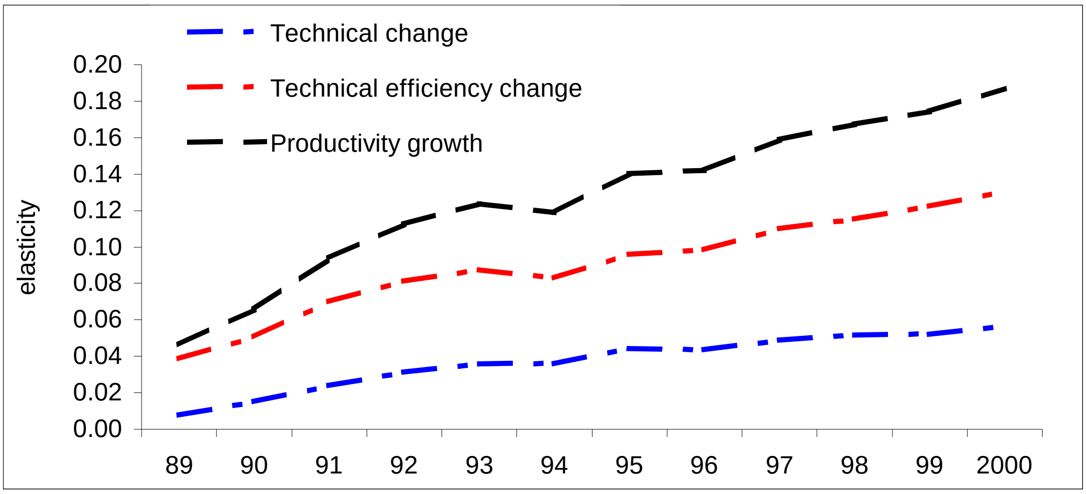

Figure 3: Technical change and productivity growth (1989-2000)

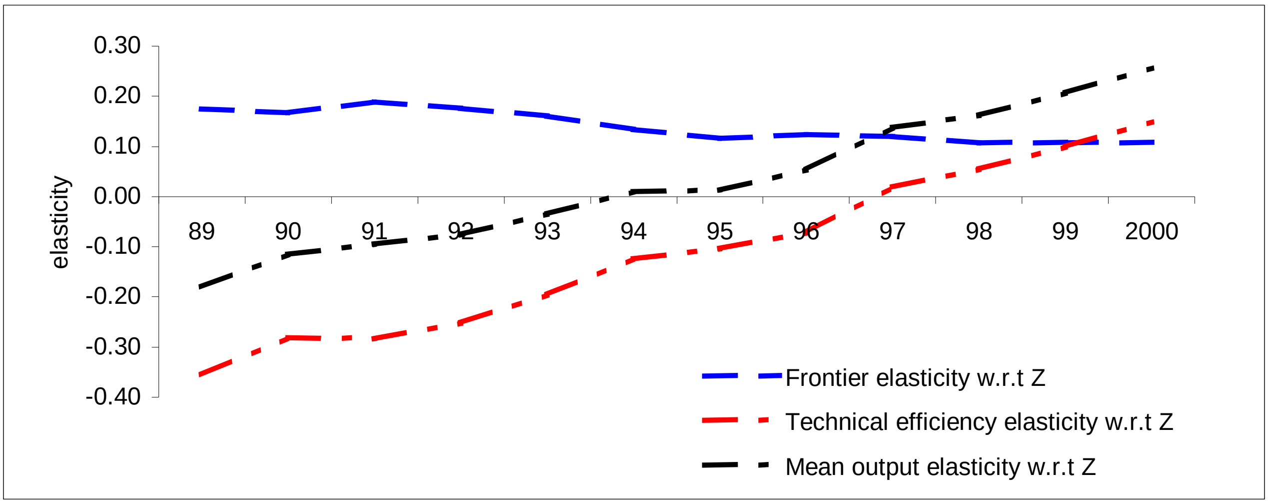

Figure 4: Change in elasticity of output with respect to Biodiversity (1989-2000)

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] 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.

[iii] Details of the optimal solution, the properties of the optimal adjustment pathway and an analysis of the impact on agricultural output of technological change and biodiversity are provided in the appendix (available on request).

[iv] Details on the construction of this index are available in the appendix (available on request).

[v] 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.

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

[vii] Details on constructing the biodiversity index, the alternative stochastic specifications and the results of testing these specifications are available in the appendix (available on request).