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A note on sustainable agricultural intensification through agro-biodiversity conservation

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This paper addresses the relationship between agro-biodiversity conservation and sustainable agricultural intensification. It shows that in biodiversity poor agro-ecosystems both agro-biodiversity and conventional input intensification may increase through optimal adjustments of input use. Increase in agro-biodiversity conservation is a necessary condition for optimal adjustment to equilibrium but whether input use will increase or decrease along this optimal path depends on the buffering effect of agro-biodiversity on ecosystem damage and the relative welfare impacts of output reductions and ecosystem damage. The model points out that ecosystem damage (through agro-biodiversity loss) can decline even under increased agricultural intensification.

KEYWORDS: Agrobiodiversity, sustainable agricultural intensification, ecosystems

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1. Introduction

It is widely accepted that agricultural productivity must increase to cope with the increasing food demands from a rising population against a background of relatively inflexible cultivable land area. At the same time it is recognised that the modern intensive agricultural practices, that have been the main source of productivity gains in recent decades, may not be sustainable (McNeely and Scherr; Mooney, Cooper and Reid; Jackson, Pascual and Hodgkin). Further, as people confront population growth, increased food demand, climate change, and the globalization of agricultural markets, agricultural landscapes are undergoing unprecedented transitions. Thus we face a challenge of raising productivity without compromising the flow of valuable ecosystem services (MEA; Perrings et al.; FAO)

A key issue here is the contrast between two views of the interactions between agricultural production and ecological processes. On the one hand the competitive vision of agricultural production that has dominated agricultural practice in industrial countries, supports an approach that adjusts the environment so that growing conditions for a target species (the ‘crop’) are optimised while those for competing species (e.g. ‘weeds’ and ‘pests’) are deliberately worsened. This approach is now being questioned since it ignores well-known interactions between species as well as a range of processes that contribute to short and long-term agricultural productivity (Altieri; Swift Izac, and van Noordwijk). The alternative view suggests that long run productivity is more likely related to maintenance of specific ecosystem functions rather than the number of species per se. Further, agro-biodiversity is likely to enhance agro-ecosystem functioning when assemblages of species are added whose presence results in unique or complementary effects on ecosystem functioning (Tscharntke et al.; Jackson, Pascual and Hodgkin)

These contrasting effects indicate an ambiguous relationship between productivity and agro-biodiversity since the conservation of non-crop species introduces a trade-off between increased direct competition with crop species (for land, light, nutrients, moisture etc.) and the increased support that these species provide for agro-ecosystem functions (such as nutrient recycling, biological pest control, pollination etc.) that promote crop productivity. In fact, there is a growing interest in empirically analysing the productivity effect of agro-biodiversity in the short and long run. Studies seem to confirm that agro-biodiversity is instrumental to increasing the mean level while at the same time decreasing the variance of crop yields (e.g., Smale et al.; di Falco and Chavas, di Falco and Perrings) and also adds to technical efficiency in farming (Omer, Pascual and Russell). This concurs with experimental and observational ecological studies about the role of agro-biodiversity for the stability and productivity of agricultural biomass (Loreau et al.). Additionally, there are some emergent theoretical studies that create stylised ecological-economic frameworks to better understand the role of biodiversity in agriculture (e.g. Baumgärtner and Quaas). Our study also uses a stylised representation of an agro-ecosystem. It deals with the relationship between increasing use of inputs and the stock of biodiversity, and addresses the problem of sustainable intensification. Specifically we address the role of agro-biodiversity conservation as a means of enhancing the buffering capacity of an agro-ecosystem. This supports the sustainable intensification of agricultural production processes along an optimal pathway that generates maximum economic welfare. To our knowledge no other study has yet addressed these issues.

Here we address this relationship theoretically and spell out the conditions that are necessary for finding a positive relationship between agro-biodiversity conservation and agricultural intensification. The model shows that these conditions occur in quite general circumstances where there is (1) an agricultural production technology that supports a positive relationship between ecological integrity of a given agricultural area and agricultural productivity in that area, and (2) decision maker preferences that recognise this positive relationship and generate resource allocation decisions that support it.

The model is structured as follows. The next section builds up the model and then Section 3 offers a qualitative analysis of the optimal dynamic relationship between agricultural output and agro-biodiversity levels. Then section 4 further addresses the relationship between ecosystem damage and input intensification along the optimal path. Finally section 5 concludes.

2. The model

The present model focuses on maximizing the discounted present value of utility flows to perpetuity where utility is assumed to depend on a sustained flow of marketable agricultural output, *Y(t)*, with disutility arising from agro-ecosystem damage, *D(t).* The latter is related to the use of artificial inputs, *X(t)*. For the decision maker, the problem becomes to optimally allocate resources on a given area of land at any period *t,* between marketable agricultural output, *Y(t)*, and environmental conservation effort or expenditures, *C(t),* in order to enhance the current biodiversity stock, *B(t).*

The direct utility function, *U=U[Y(t),D(t)],* is assumed strictly concave, linearly separable in *Y* and *D*, and with positive and diminishing marginal utility with respect to *Y(t)* i.e. $U_Y > 0, U_{YY} < 0$. In addition, the marginal utility of *D(t)* is specified to be negative and decreasing; $U_D < 0, U_{DD} < 0$.

2.1. Agro-biodiversity and agro-ecosystem damage

The stock of agrobiodiversity, *B(t),* enters into the production function alongside the vector of artificial inputs, *X(t),* thus assuming that biodiversity is a natural input favouring crop production. The agricultural production function, *F[X(t),B(t)]*, is assumed to be strictly concave and twice differentiable, with $F_B > 0, F_{BB} < 0$ and $F_X > 0, F_{XX} < 0$, and to exhibit weak essentiality, $F(0) = 0$. Due to the ambiguous nature of the relationship between agricultural productivity and biodiversity, linear separability is assumed between *X* and *B*. The latter separability assumption is used due to the indefinite scale of the present analysis; a given 'area of land' is consistent with a range of possibilities from field/farm level to watershed/region level. Since each level has a set of sub-components and hence a different interaction with production process, the main effect of a change in stock of biodiversity, *B(t)*, on the marginal product of artificial input, *X(t),* is likely to be different at each level or sublevel of *B(t)*. For instance, an increase in the diversity of insects or soil micro-organisms is assumed to increase the marginal product of artificial input use, e.g. fertiliser, since it is expected to enhance the soil productivity, i.e. $F_{XB} \geq 0$. Alternatively, an increase in natural vegetation diversity would decrease the marginal product of fertiliser as it increases the competition against the cultivated crops, giving $F_{XB} \leq 0$. Similar examples could be stated for other components of biodiversity. Generally to determine the effect of an increase in B*(t)* on marginal product of *X(t)*, requires detailed and specific information on which component(s) of biodiversity is changed. Hence, for simplicity, *F[X(t), B(t)]*, is assumed to be linearly separable in *B(t)* and *X(t).* i.e. $F_{XB} = F_{BX} = 0$.

The effect on agro-ecosystem services of intensified agricultural production is represented by the 'damage (or 'degradation') function', *D(t)=D[X(t), B(t)]*, to reflect that the dynamics of such ecosystem service degradation is density dependent. In this case, we assume that increasing the stock of biodiversity makes a positive contribution to ecosystem resilience and hence to its ability to better tolerate and overcome the adverse effect of agricultural activities, hence $D_B < 0, D_{BB} > 0$. In addition, ecosystem damage due to application of *X* is assumed to rise at an increasing rate, i.e. $D_X > 0, D_{XX} > 0$.

However the secondary relationship between the impact of *X* on ecosystem service degradation and the stock of biodiversity (i.e. the sign of D_{XB}) is harder to ascertain. On the one hand this relationship may be negative as an increase in biodiversity stock increases resilience of the agro-ecosystem and also reduces the damage generated by any given level of *X* application. On the other hand the increased biodiversity stock could become more accessible and thus more vulnerable to being damaged by increasing *X,* suggesting a positive relationship. Given this ambiguity, the damage impact function is made linearly separable in *X(t)* and *B(t)*, i.e. $D_{XB} = D_{BX} = 0$.

The state variable, *B(t),* is assumed to evolve according to a process reflecting (i) the natural dynamics of biodiversity, (ii) purposive biodiversity conservation activities, and (iii) conventional agricultural activities carried out in the agro-ecosystem using conventional inputs, yielding the following simple extended logistic function:

(1a) $$\dot{B} = \alpha B(1 - B/K) + \delta C - \gamma X$$

where $\alpha > 0$ might reflect the natural dynamics of B, and *K* stands for the maximum diversity that can be obtained in the land area under a given natural evolution without artificial input application, echoing the idea of a carrying capacity for *B*. As in highly intensified agricultural systems it is typical to find relatively low levels of biodiversity compared to *K*, the term *B/K* is expected to be negligible, and without loss of generality, equation (1a) can be approximated as:

(1b) $$\dot{B} = \alpha B + \delta C - \gamma X$$

where α, δ and γ are all constants. Equation (1b) shows that biodiversity is enhanced proportionally to investment in conservation, C, δ being the rate of induced growth[1], and that biodiversity is degraded proportionally to artificial input application. In addition, it is assumed that no depletion in biodiversity occurs as a result of its support to the production process.

2.2. The maximum principle

The objective is to choose the time paths for the control variables, *X(t)* and *C(t)*, that maximise the value function, *W*, considering the instantaneous effect on utility, and the inter-temporal impact on the state of biodiversity. This is in effect a problem of identifying the trade-off between consumption and biodiversity conservation that involves optimising the production process by controlling the scale of agricultural intensification, *X(t).* The problem is described as:

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

where $\rho > 0$ is the utility discount rate, subject to (i) the equation of motion for *B(t),* (ii) the non-negativity constraints, i.e. $X \geq 0$ and $D \geq 0$, (iii) the initial condition $B(0) = B_0$, (iv) the impact function *D(.),* and (v) the environmental conservation investment function (3):

(3) $$C(t) = F[X(t), B(t)] - Y(t)$$

This yields the current-value Hamiltonian:

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

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

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

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

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

(5d) $$\dot{\varphi} = -U_D D_B - \varphi(\alpha + \delta F_B - \rho) = -\frac{\partial H_C}{\partial B} + \rho\varphi$$

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 *B(t)* equals its marginal cost.

3. Qualitative analysis

In order to gain analytical insights into the dynamic behaviour of the relationship between agriculture and its impact on biodiversity, a qualitative analysis that focuses on *BY* space for this agro-ecological system and a differential equation for *Y*, is derived from the optimal solution. From (5b-5c) *X* can be defined as an implicit function of *Y* and *B* giving equation (6), with $X_B > 0$ and $X_Y < 0$, i.e. *X (Y, B)* is the level of *X* that solves the optimality conditions.

(6) $$U_Y[\delta F_X - \gamma] + \delta U_D D_X = 0$$

In addition, the optimal path for *Y* is derived from the Maximum Principle by totally differentiating (5b) with respect to time[2]:

(7) $$\dot{Y} = -\frac{U_Y}{U_{YY}}\left[\alpha - \rho + \delta F_B - [\delta F_X - \gamma]\frac{D_B}{D_X}\right]$$

Equation (7), together with the state equation (5a), gives a new set of non-linear dynamic relationships for this agro-ecological system, with *Y(0)* left free. To examine the dynamic behaviour of the system in (*B*, *Y*) space a phase diagram can be constructed.(c.f. Figure 1).

The dynamic system, at equilibrium is denoted as:

$$\dot{B} = g(B,Y)$$
$$\dot{Y} = f(B,Y)$$

This system is assumed to have a unique solution that satisfies the initial conditions $B(0) = B_0$. Two demarcation curves (isoclines) ($\dot{B} = 0$ and $\dot{Y} = 0$) are drawn, that divide the phase space into four regions (I to IV), with a different mix of time derivatives for *Y(t)* and B*(t)*.

[FIGURE 1 around here]

As regards the slopes of the biodiversity and agricultural output isoclines, $\dot{B} = 0$ and $\dot{Y} = 0$, respectively, they are given by their implicit functions $\left.\frac{dY}{dB}\right|_{\dot{B}=0} = -\frac{g_B}{g_Y}$, and $\left.\frac{dY}{dB}\right|_{\dot{Y}=0} = -\frac{f_B}{f_Y}$

where, recalling (5a), at $\dot{B} = 0$, $g(B,Y) = \alpha B(t) + \delta F(.) - \delta Y - \gamma X$, and

(8a) $$g_B = \alpha + \delta F_B + (\delta F_X - \gamma)X_B > 0$$

(8b) $$g_Y = -\delta + [\delta F_X - \gamma]X_Y < 0$$

and $(\delta F_X - \gamma) > 0$ from (5c)[3]. Additionally, since $g_Y < 0$, as Y increases $\dot{B}$ undergoes a steady decrease. As $(-U_Y / U_{YY}) > 0$ in equation (7), the $\dot{Y} = 0$ agricultural output isocline is given by:

$$f(B,Y) = \alpha - \rho + \delta F_B - [\delta F_X - \gamma]\frac{D_B}{D_X}$$

hence:

(9a) $$f_B = \delta F_{BB} - \left[\frac{[\delta F_X - \gamma]D_X D_{BB} + \delta D_X D_B F_{XX} X_B - [\delta F_X - \gamma]D_B D_{XX}}{(D_X)^2}\right] < 0$$

and

(9b) $$f_Y = -\frac{[\delta D_X D_B F_{XX} - [\delta F_X - \gamma] D_B D_{XX}] X_Y}{(D_X)^2} > 0$$

The signs of (9a) and (9b) imply that the $\dot{Y} = 0$ isocline is also upward sloping to the right. Also, $f_Y > 0$ implies that as *Y* increases $\dot{Y}$ undergoes a steady increase.

We assume that $-f_B/f_Y > -g_B/g_Y$, so that the output isocline is steeper than the biodiversity isocline in the neighbourhood of the steady state. At E both variables (*B* and *Y*) are stationary, but at any other point either *B* or *Y* (or both) would be changing over time as shown by the directional arrows in Figure 1. It can be concluded from the pattern of streamlines in these phase diagrams that the equilibrium is a saddle point as long as $-f_B/f_Y > -g_B/g_Y$. In the opposite case (i.e. , when $-f_B/f_Y < -g_B/g_Y$), the system would show no local stability (see Appendix).

The qualitative analysis focuses on the properties of key variables along the converging path illustrated by Isosector I[4]. In particular we look at the dynamics of agricultural input use as it adjusts towards equilibrium over time, $\dot{X}$, and the corresponding adjustment of ecosystem service degradation, $\dot{D}$.

4. The relationship between ecosystem damage and input intensification

The optimal adjustment of agricultural input use is described by the following expression[5]:

(10) $$\dot{X} = \frac{\{[\delta F_X - \gamma] U_{YY} \dot{Y} + \delta U_{DD} D_X D_B \dot{B}\}}{\{-\delta U_Y F_{XX} - \delta U_D D_{XX} - \delta U_{DD} (D_X)^2\}} \equiv \frac{N_1 + N_2}{L}$$

According to the sign conventions previously adopted, it can be shown that while the denominator (*L*) in (10) is positive, the sign of the numerator is ambiguous.

The first term in the numerator, $\mathrm{N}_1 \equiv (\delta F_X - \gamma) U_{YY} \dot{Y} < 0$, can be rewritten as $(\delta F_X - \gamma)\eta_Y U_Y \frac{\dot{Y}}{Y} < 0$, where $\eta_Y = Y(U_{YY}/U_Y)$ measures the elasticity of marginal utility of output. This elasticity shows the percentage change in marginal utility for a one per cent change in output and can be interpreted as a measure of how tolerant the decision maker is to reductions in agricultural output. Intuitively this would be measured by the extent to which declining utility levels due to reductions in output are cushioned by offsetting changes in the marginal utility of output. This term represents the 'weighted' effect of a change in *X* on utility, through its impact on biodiversity stock and output, where the weight is the rate of output growth $\dot{Y}/Y$. Given the assumptions about the nature and derivatives of the functions in the model (see section 2), this term is negative.

In a similar way $N_2 \equiv \delta U_{DD} D_X D_B \dot{B} > 0$ may be rewritten as $\delta D_X \psi_{DB} \eta_D U_D \frac{\dot{B}}{B}$ where $\eta_D = D(U_{DD}/U_D)$ measures the elasticity of marginal utility of ecosystem damage (the decision maker's tolerance to ecosystem damage) and $\psi_{DB} = D_B \frac{B}{D}$ measures the damage elasticity with respect to *B*. The latter elasticity shows the percentage reduction in ecosystem damage for each percentage increase in biodiversity and thus reflects the relative impact of changes in biodiversity stock in cushioning ecosystem damage. This second term in the numerator represents the 'weighted' effect of a change in *X* on utility, through its impact on biodiversity stock and ecosystem damage, where the weight is the rate of growth in the stock of agro-biodiversity $\dot{B}/B$. Given the assumptions detailed in section 2, this term is positive.

Input use will be increasing along the optimal adjustment path ($\dot{X} > 0$) whenever $N_2 > N_1$ and the numerator as a whole is positive. This will depend on the extent to which the decision maker is either less tolerant to reductions in output (N_1 smaller) or more tolerant to increases in ecosystem damage (N_2 larger) where tolerance is measured by the extent to which reductions in utility occasioned by either of these changes is cushioned by offsetting changes in the corresponding marginal utilities. The implication is that preferences displaying greater tolerance to ecosystem damage (or less tolerance to reductions in output) would tend to support increased input use along the optimal path to equilibrium and thus the intensification of agricultural production processes. This tendency would be further supported in an agro-ecological system where the damage elasticity of biodiversity is greater (increasing the value of N_2 above) so that biodiversity has a greater cushioning impact on ecosystem damage.

We also investigate the relationship between optimal agro-ecosystem degradation and agricultural intensification by considering the optimal co-evolution of $\dot{X}$ and $\dot{D}$ along the convergent path in this Isosector. Totally differentiating the damage function, *D (X,B),* with respect to time, i.e., $\dot{D} = D_X \dot{X} + D_B \dot{B}$, the effect of the change in inputs on *D* along the optimal path, can be derived by substituting for $\dot{X}$ from equation (6), obtaining the following equation of motion for ecosystem damage as a function of agroecological effects, the motion of biodiversity and agricultural output and their effects on utility:

(11) $$\dot{D} = \frac{\left\{\left[\delta U_D D_{XX} + \delta U_Y F_{XX}\right] D_B \dot{B} - \left[\delta F_X - \gamma\right] D_X U_{YY} \dot{Y}\right\}}{\left\{\delta U_Y F_{XX} + \delta U_D D_{XX} + \delta U_{DD} \left(D_X\right)^2\right\}}$$

From (11) and based on the assumptions about the nature and derivatives of the functions in the model (see section 2), $\dot{D}$ is unambiguously negative where both $\dot{B} > 0$ and $\dot{Y} > 0$, i.e. for a biodiversity-poor agro-ecosystem that could be represented by Isosector I.

That is, in Isosector I $\dot{D} < 0$ and this will be the case even when $\dot{X} > 0$. It implies that along the optimal path to the long run equilibrium, in biodiversity poor agricultural landscapes, ecosystem damage would decline even when input use increases. The point is thus that along the optimal path, at relatively low levels of biodiversity, increasing input use can be consistent with reductions in ecosystem degradation. This result is more likely to arise when biodiversity stock has a strong cushioning effect on ecosystem damage and when decision maker preferences show greater tolerance for ecosystem damage and less tolerance for reductions in output.

5. Conclusions

The theoretical model presented here rests on some stylized assumptions regarding the role of agro-ecosystem on a fixed area of land. According to such assumptions it is possible to show that in principle it should be possible to find an optimal path of agricultural intensification that is consistent with a reduction in ecosystem damage (or lowering agro-biodiversity loss) as the systems adjusts towards the long run equilibrium. This trajectory would maximise welfare for a decision maker over time. In this vein we show that (1) decreasing ecosystem damage is a key characteristic of this adjustment and that (2) only in certain circumstances this can be accompanied by an increase in the use of artificial inputs leading to intensification of agricultural production processes. While the former result is unsurprising, this latter result suggests that there should be room to explore the existence and the conditions accompanying sustainable agricultural intensification processes.

This result relates to farming systems where agro-biodiversity has been greatly depleted. Thus, the potential for recovering higher levels of agro-biodiversity through conservation activities while at the same time trying to enhance agricultural production is possible. More specifically, while a decrease in ecosystem damage is a characteristic of the optimal adjustment path across all the circumstances allowed by the current model, whether input use will increase or decrease as the ecosystem optimally adjusts along this pathway will depend on the nature of the production technology used and on the preferences of the decision maker. Increasing input use (intensification) is most likely to arise as an optimal strategy where the existing low levels of biodiversity have a greater impact in cushioning ecosystem damage so that the ecosystem is more resilient to damage from agricultural production processes. Sustainable intensification is also more likely to arise when the decision maker is more tolerant to ecosystem damage and less tolerant to reductions in available output, where tolerance is measured by the elasticity of marginal utility with respect to output and ecosystem damage respectively. This is a key parameter that provides an index of the extent to which the effects on utility, of changes in output and ecosystem damage, are cushioned by offsetting changes in marginal utility.

The result implies that the sustainable intensification of agricultural production processes, that would help support security of food supply in the face of increasing demands from an increasing and increasingly affluent population under further competition for agricultural land, could be facilitated by policies that encouraged agro-ecosystem resilience and greater tolerance by the decision maker to ecosystem damage.

While the analysis is consistent with policies that are aimed at reducing ecosystem damage (e.g., environmental stewardship schemes of the CAP in the EU), the implications go further than this and show first of all (especially for regions in developing countries that have become highly intensified at the expense of agro-biodiversity), change in agricultural production practices that enhances the buffering influence of biodiversity on ecosystem damage could promote food security, even in the short term, by supporting sustainable intensification. This lends support to further expanding the call for research on agro-ecosystems and environmentally friendly farming systems (Altieri; Perrings et al.; Jackson, Pascual and Hodgkin). Ultimately the feasibility of sustainable intensification will depend on the relative extent to which welfare responds to ecosystem damage versus potential reductions in agricultural output. It is not clear whether this characteristic of individual and societal preferences might be altered by information and education programmes.

Footnotes/Endnotes

1. The parameter δ can also be interpreted as the marginal degradation in *B(t)* caused by increase in *Y(t)* i.e. the opportunity cost of *C(t)*.

2. See the Appendix for a full illustration of the two partial derivatives. In addition the second order conditions, required for optimality of this solution are met, i.e. both the utility and production functions are strictly concave.

3. Concavity arises from the fact that $\dot{B}=0$ leads to $Y = F(.) + \frac{\alpha}{\delta}B - \frac{\gamma}{\delta}X$, therefore the locus of $\dot{B}=0$ exhibits the same curvature as that of the production function.

4. There is also a converging path in Isosector III where initial levels of biodiversity are higher and convergence requires that both biodiversity and output decline over time. Analysis of relationships in this Isosector, that could be relevant to biodiversity-rich agro-ecosystems, is not the focus of this paper.

5. This expression is obtained by totally differentiating equation (6) with respect to time and rearranging terms.

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Appendix: Details of the Mathematical Analysis

The Partial Derivatives of the Implicit Function, X(B,Y):

Equation. (6) is relabelled as (A1):

(A1) $$U_Y\left[\delta F_X - \gamma\right] + \delta U_D D_X = 0$$

Eq (A1) is differentiated w.r.t *Z*, and rearranging:

(A2) $$X_B = \frac{-\delta U_{DD} D_B D_X}{\left[\delta U_Y F_{XX} + \delta U_{DD}\left(D_X\right)^2 + \delta U_D D_{XX}\right]} > 0$$

By differentiating (A1) w.r.t *Y* and rearranging:

(A3) $$X_Y = \frac{\left[\delta F_X - \gamma\right] U_{YY}}{\left[-\delta U_Y F_{XX} - \delta U_{DD}\left(D_X\right)^2 - \delta U_D D_{XX}\right]} < 0$$

The denominator is positive and the numerator is negative, as $\left(\delta \partial F/\partial X - \gamma\right) > 0$ by (5c).

Transversality Conditions:

The optimal path satisfies the following transversality conditions:

(A4.a) $$\lim_{t\to\infty} \mu(t) = 0 \quad \text{i.e. } \mu(t) \to 0 \text{ as } t \to \infty$$

Equation (5b, Section 2) gives the solution path of $\mu(t)$ as

(A4.b) $$\mu^* = \frac{1}{\delta}\frac{\partial U}{\partial Y^*} e^{-\rho t}$$

Equation (A4.b) implies that for U_Y to tend to infinity, *Y* must approach to zero. However, in this model *Y** does not tend to zero as *t* approaches infinity since setting $\partial H_C / \partial Y = 0$ rules out any corner solution. The exponential term tends to zero, as *t* goes to infinite. Therefore, the first transversality condition is satisfied. The second transversality condition is

(A4.c) $$\lim_{t\to\infty} H = 0 \quad \text{i.e. } H \to 0 \text{ as } t \to \infty$$

For the specified problem, the solution path of *H* is

(A4.d) $$H^* = U(Y^*, D^*)e^{-\rho t} + \mu^*(\alpha B^* + \delta F(.) - \delta Y^* - \gamma X^*)$$

$U(.)e^{-\rho t}$ tends to zero as when *t* goes to infinite. The bracketed expression in the second term, i.e. the state equation, is zero by the definition of the steady state. Therefore, the second transversality condition (ii) is also satisfied.

Sufficient Conditions for optimality:

If the Hamiltonian is strictly concave, then the maximum principle is sufficient for a unique global maximum. The Hessian matrix of the Hamiltonian is

(A5.a)

$$H = \begin{bmatrix} H_{XX} & H_{XY} & H_{XB} \\ H_{YX} & H_{YY} & H_{YB} \\ H_{BX} & H_{BY} & H_{BB} \end{bmatrix}$$

where:

$$H_{XX} = U_{DD}(D_X)^2 + U_D D_{XX} + \varphi\delta F_{XX} < 0$$

$$H_{XY} = 0$$

$$H_{XB} = U_{DD} D_X D_B$$

$$H_{YX} = 0$$

$$H_{YY} = U_{YY}$$

$$H_{YB} = 0$$

$$H_{BX} = U_{DD} D_X D_B > 0$$

$$H_{BY} = 0$$

$$H_{BB} = U_{DD}(D_B)^2 + U_D D_{BB} + \varphi\delta F_{BB} < 0$$

$$H_{BB} = U_{DD}(D_B)^2 + U_D D_{BB} + \varphi\delta F_{BB} < 0$$

After rearranging, the Hessian determinant is given by:

(A5.b)
$$|H| = [U_D D_{XX} + \varphi\delta F_{XX}][U_{YY}U_{DD}(D_B)^2 + U_{YY}U_D D_{BB} + \varphi\delta U_{YY}F_{BB}] + U_{DD}(D_X)^2[U_{YY}U_D D_{BB} + \varphi\delta U_{YY}F_{BB}] < 0$$

To verify that the supplementary condition, $\lim_{t\to\infty}\mu(t)[B(t) - B^*(t)] \geq 0$, also holds, it is shown above that the transversality condition $\lim_{t\to\infty}\mu(t) = 0$ is also satisfied. Hence, regardless whether the term (*B (t) – B*(t)*) is bounded or tends to zero as *t* goes to infinity, this condition is satisfied as an equality since *μ(t)* tends to zero as *t* tend to infinity. Consequently, given the concavity of the Hamiltonian, the maximum principle is sufficient for a global maximum.

Local Stability Analysis

The characteristic roots of the linearised differential-equation system ($\dot{B}, \dot{Y}$) are examined:

(A6.a)
$$\dot{B} = \alpha B + \delta F(.) - \delta Y - \gamma X$$

(A6.b)
$$\dot{Y} = -\frac{U_Y}{U_{YY}}\left[\alpha - \rho + \delta F_B - [\delta F_X - \gamma]\frac{D_B}{D_X}\right]$$

The linearised system of the differential through a Taylor expansion around the steady state ($\bar{B}, \bar{Y}$), where t $J_d\begin{bmatrix}\bar{B}\\ \bar{Y}\end{bmatrix}$ is constant is given by:

(A7)
$$\begin{bmatrix}\dot{B}\\ \dot{Y}\end{bmatrix} - \begin{bmatrix}\dot{B}_B & \dot{B}_Y\\ \dot{Y}_B & \dot{Y}_Y\end{bmatrix}\begin{bmatrix}B\\ Y\end{bmatrix} = \begin{bmatrix}\dot{B}\\ \dot{Y}\end{bmatrix} - J_d\begin{bmatrix}B\\ Y\end{bmatrix} = \begin{bmatrix}0\\ 0\end{bmatrix}$$

where J_d is the Jacobian matrix for this system. The two differential equations are assumed to be functionally independent i.e. $|J_d| \neq 0$. (If $|J_d| = 0$, the $\dot{B} = 0$ and $\dot{Y} = 0$ would coincide and give an infinite number of equilibrium points.) The behaviour of the phase trajectories near the equilibrium point depends on the sign of the characteristic roots of the Jacobian matrix.

(A8.a) $$\dot{B}_B = \alpha + \delta F_B + [\delta F_X - \gamma] X_B$$

(A8.b) $$\dot{B}_Y = -\delta + [\delta F_X - \gamma] X_Y < 0$$

(A8.c) $$\dot{Y}_B = -\frac{U_Y}{U_{YY}} \left\{ \delta F_{BB} - \left[\frac{[\delta F_X - \gamma]\delta D_X D_{BB} + \delta D_X D_B F_{XX} X_B - [\delta F - \gamma] D_B D_{XX} X_B}{(D_X)^2} \right] \right\}$$

(A8.d) $$\dot{Y}_Y = -\frac{U_Y}{U_{YY}} \frac{[-\delta D_X D_B F_{XX} + [\delta F_X - \gamma] D_B D_{XX}] X_Y}{(D_X)^2} > 0$$

If $|J_d| < 0$, it implies that the steady state is locally a saddle point (Figure 1). If $|J_d| > 0$, the sign of the trace of the Jacobian determinant needs to be checked to determine the type of equilibrium. However, the maximum principle solution satisfies the sufficiency conditions and therefore, the dynamic system of this model is expected to generate a saddle point equilibrium.

Figures

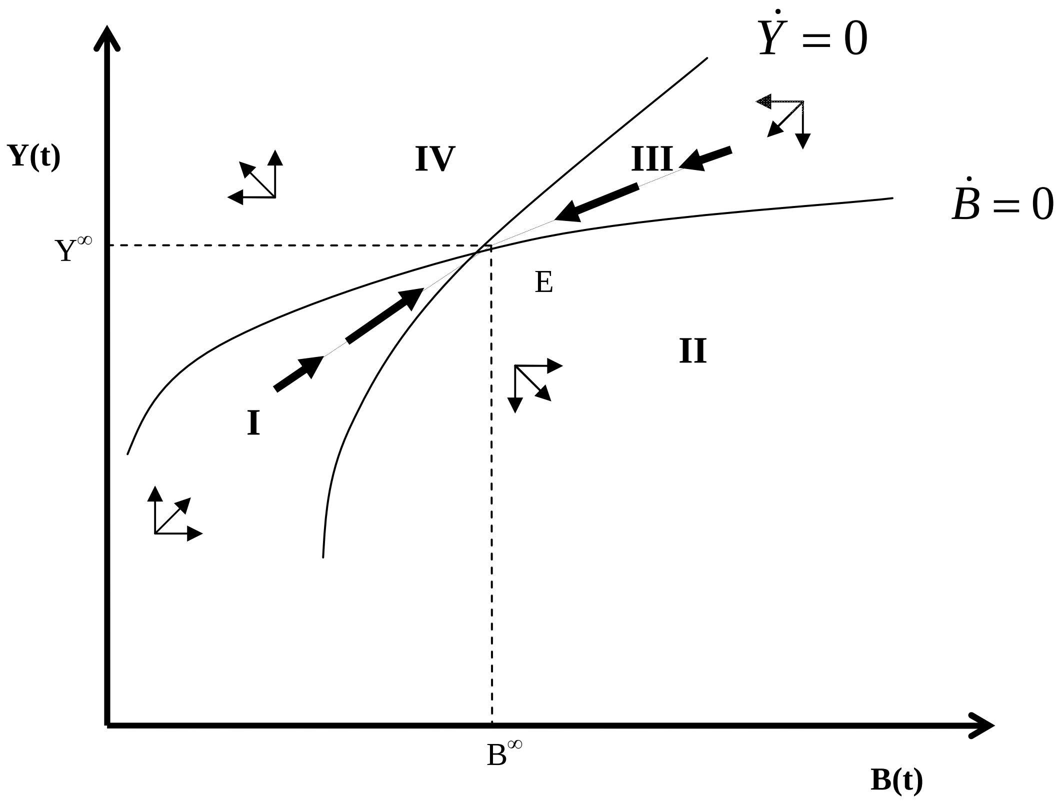

Figure 1. E as a saddle point equilibrium in *(B, Y)* phase space