



University of New England

Graduate School of Agricultural and Resource Economics

**Dynamic Models, Externalities and Sustainability
in Agriculture**

by

Oscar J. Cacho

No. 99-4 – April 1999

**Working Paper Series in
Agricultural and Resource Economics**

ISSN 1442 1909

<http://www.une.edu.au/febl/EconStud/wps.htm>

Copyright © 1999 by Oscar J. Cacho. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided this copyright notice appears on all such copies. ISBN 1 86389 579 5

Dynamic Models, Externalities and Sustainability in Agriculture

Oscar J. Cacho **

Abstract

The goal of sustainability in the management of natural resources and agricultural systems has received increasing attention during the 1990's. The many dimensions of the problem have been extensively discussed in the literature and a recognition of the interaction between economic, biological and social objectives have led to an acceptance of its multidisciplinary nature. When studying sustainability in agriculture, two aspects which cannot be ignored are (i) any measure must include economic as well as biological criteria and (ii) the dynamic nature of the production system and the environment (both physical and economic) must be accounted for.

The goal of sustainable agricultural practices at the microeconomic level is explored in this paper, in an attempt to link the individual producer behaviour to the regulatory environment. Particular attention is paid to the dynamic aspect in the context of a grazing system, where plant and animal populations interact with each other and are influenced by the environment. An optimal control formulation is used to discuss the alternative ways in which externalities (such as salinity, soil loss and fertiliser and chemical run-off) can be incorporated into a model. The problem of valuing externalities and the role of the discount rate on optimal management strategies are briefly discussed.

Key Words: sustainability, dynamic modelling, bioeconomics

** Oscar Cacho is a Senior Lecturer in the School of Economic Studies, and a Member of the Graduate School of Agricultural and Resource Economics at the University of New England. Contact information: Graduate School of Agricultural and Resource Economics, University of New England, Armidale, NSW 2351, Australia. Email: ocacho@metz.une.edu.au.

Dynamic Models, Externalities and Sustainability in Agriculture

Introduction

Definitions of the term *sustainability* and discussions of its significance abound in the literature. A cursory review reveals that much of what has been written deals with philosophical issues and questions. Gale and Cordray (1994) focus on the problem of definition and consensus, they discuss the many meanings of the term and ask what should be sustained and why, how to measure sustainability and what the political implications are. Ruttan (1994) deals with the questions of substitutability between resources, intergenerational transfers and discount rates. Dalsgaard et al. (1995) present a tentative list of ecological attributes for quantification and ranking of farming systems in terms of sustainability, including diversity, cycling, stability and capacity. Cai and Smit (1994) discuss the different spatial scales in which sustainability must be measured (from the field to the globe) and argue that a different set of analytical questions must be answered depending on the scale being measured; they contend that achievement of sustainable agriculture must eventually involve an integration of all the spatial scales. De Wit et al. (1995) discuss general criteria for sustainable livestock production, they point out to the importance of dynamic processes and emphasise the multi-objective nature of the problem, which makes it difficult to state that one system is more sustainable than another as the score assigned to a given system may differ according to the criterion being measured.

When dealing with sustainability in agriculture, there is a general acceptance of the multidisciplinary nature of the problem stemming from the interaction between economic, biological and social objectives. There also seems to be general agreement on the fact that, on a local scale, sustainability must be defined and measured at the system level. That is, we cannot expect a single crop or livestock enterprise to be sustainable by itself, but we can speak of a given farming system as being sustainable, this would generally include a series of crop rotations and livestock enterprises. The recent book by Barnett et al. (1995) is one of the first attempts to measure agricultural sustainability, the book contains papers by several authors who estimate total social factor productivity from data obtained in long term agronomic experiments; they define sustainability as *non decreasing total social factor productivity and non decreasing profitability* (Barnett et al. , 1995).

In this paper the various aspects of sustainability in agriculture are explored by developing a relative simple dynamic model, the model is used to focus on the problems of discounting, measurement of externalities and possible ways in which government policies can stimulate the development and adoption of sustainable production systems. However it is defined, sustainable agriculture is concerned with the ability of agricultural systems to remain productive in the long run. Definitions of sustainability relevant to this paper include: *the ability of the agroecological system to maintain productivity in the face of stress or shocks* (Conway and Barbier, 1988); and *an improvement in the productive performance of a system without depleting the natural resource base upon which future performance depends* (Pearce et al., 1990; Pandey and Hardaker, 1995).

A General Model

When studying sustainability in agriculture, two aspects which cannot be ignored are (i) any measure must include economic as well as biological criteria and (ii) the dynamic nature of the production system and the environment (both physical and economic) must be accounted for (Cacho, 1995). In this section a general model of resource use in agriculture is presented. The model is based on that of Pandey and Hardaker (1995), but it is expressed as an optimal control problem in continuous time, it contains one state variable and one control variable and can be readily extended to account for additional variables. In principle, the farmer's decision problem is:

Max

$$J = \int_{t=0}^T b(u_t, x_t) e^{-rt} dt \quad (1)$$

Subject to:

$$\dot{x}_t = \frac{d}{dt}x_t = g(u_t, x_t) \quad (2)$$

$$x(0) = x_0 \quad (3)$$

$$x(T) \geq x_0 \quad (4)$$

Where J is a discounted cumulative performance measure over the planning horizon T , b is a measure of farm performance, x is stock of a natural resource (state variable), u is a management decision (control variable), r is the discount rate and g is the rate of growth (or depletion) of the resource through time. Constraint (4) ensures that the system is sustainable in the sense that the final stock of the resource is no less than the initial stock.

The Hamiltonian for this problem is:

$$H_t = b(u_t, x_t)e^{-rt} + \mathbf{I}_t g(u_t, x_t) \quad (5)$$

and the solution is obtained by solving the system:

$$\frac{d}{du}H_t = e^{-rt}b_u(u_t, x_t) + \mathbf{I}_t g_u(u_t, x_t) = 0 \quad (6)$$

$$\frac{d}{dx}H_t = e^{-rt}b_x(u_t, x_t) + \mathbf{I}_t g_x(u_t, x_t) = -\dot{\mathbf{I}} \quad (7)$$

$$\frac{d}{d\mathbf{I}_t}H_t = g(u_t, x_t) \quad (8)$$

The transversality conditions, required to obtain a unique solution, are:

$$\mathbf{I}(T) \geq 0, \quad x(T) \geq x_0, \quad (x(T) - x_0)\mathbf{I}(T) = 0 \quad (9)$$

To implement a working model of a specific system, the functions b and g must be defined. A typical example of g is a soil erosion model, while a common example of b is a profit function. The solution to this problem yields three optimal trajectories through time $(u_t^*, x_t^*, \mathbf{I}_t^*)$ which maximise (1) while ensuring that the final stock of resources is not below the initial stock (x_0).

Conditions (6) and (7) must be satisfied for the interval $0 \leq t \leq T$, thus (dropping the t subscripts to avoid clutter) we have:

$$(e^{-rt}b_{uu} + \mathbf{I}g_{uu})\dot{u} + (e^{-rt}b_{ux} + \mathbf{I}g_{ux})\dot{x} + g_u\dot{\mathbf{I}} = re^{-rt}b_u \quad (10)$$

$$(e^{-rt}b_{xu} + \mathbf{I}g_{xu})\dot{u} + (e^{-rt}b_{xx} + \mathbf{I}g_{xx})\dot{x} + g_x\dot{\mathbf{I}} + \ddot{\mathbf{I}} = re^{-rt}b_x \quad (11)$$

Which can be expressed as:

$$\begin{bmatrix} b_{uu} + \mathbf{I}g_{uu} & b_{ux} + \mathbf{I}g_{ux} \\ b_{xu} + \mathbf{I}g_{xu} & b_{xx} + \mathbf{I}g_{xx} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{x} \end{bmatrix} = \begin{bmatrix} rb_u - e^{rt}\dot{\mathbf{I}}g_u \\ rb_x - e^{rt}(\dot{\mathbf{I}}g_x + \ddot{\mathbf{I}}) \end{bmatrix} \quad (12)$$

where $\mathbf{q} = e^{rt} \mathbf{I}$. Using Cramer's rule we obtain:

$$\dot{x} = \frac{(b_{uu} + \mathbf{q}g_{uu})(rb_x - e^{rt}(\dot{\mathbf{I}}g_x + \ddot{\mathbf{I}})) - (b_{xu} + \mathbf{q}g_{xu})(rb_u - e^{rt}\dot{\mathbf{I}}g_u)}{(b_{uu} + \mathbf{q}g_{uu})(b_{xx} + \mathbf{q}g_{xx}) - 2(b_{xu} + \mathbf{q}g_{xu})} \quad (13)$$

Expression (13) can be used to proceed with comparative dynamics analysis. By differentiating the function with respect to the relevant variables, we can study the effects of discount rates, prices, government policies and biophysical parameters on the rate of resource use. The complexity of the functions involved, however, precludes the usefulness of further analytical derivations. To carry the analysis further it would be necessary to develop a numerical model.

A Grazing System Model

A simple model, which describes the interaction between animals, pastures and soils in a grazing system, is developed in this section. The model is then used to discuss ways in which externalities might be accounted for. Consider a firm which produces a single output (meat) using an intermediary input (grass), a purchased input (fertiliser) which may cause an externality, and a hired input (labour). The production function is:

$$M = m(S, G) \quad (14)$$

Where M is meat produced over a given period of time, S is stocking rate and G is pasture cover (grass available for animal consumption and which protects the soil from erosion). The production function is assumed to be well behaved (continuous, differentiable and concave in S and G). The objective of the producer is assumed to be the maximisation of discounted accumulated profits over the planning horizon:

Max

$$J = \int_{t=0}^T e^{-rt} [P_M M(t) - W_N N(t) - W_L L(t)] dt \quad (15)$$

subject to:

$$\dot{D}(t) = d(D(t), G(t), R(t)) \quad (16)$$

$$\dot{F}(t) = f(F(t), N(t), G(t)) \quad (17)$$

$$\dot{G}(t) = g(G(t), S(t), N(t), D(t), R(t)) \quad (18)$$

$$D(0) = D_0 \quad (19)$$

$$F(0) = F_0 \quad (20)$$

$$G(0) = G_0 \quad (21)$$

$$D(t) \geq D_0 \quad (22)$$

$$F(T) \geq \quad (23)$$

Where D is soil depth, F is soil fertility, G is pasture mass, S is stocking rate (animals per hectare), N is nitrogen application, L is labour hired, R is rainfall, P_M is the price of meat, W_N is the price of fertiliser and W_L

Constraints (22) and (23) force the system to be sustainable with respect to soil depth and soil fertility. It should be noted that the equations of motion (16) to (18) single equations or by detailed simulation models to be solved numerically.

Labour requirements depend on stocking rate and the amount of fertiliser applied:

$$L(t) = l(S(t), N(t)) \quad (24)$$

with both l_S and $l_N \geq 0$. The Hamiltonian for this problem is:

$$H(t) = e^{-rt} [P_M M(t) - W_N N(t) - W_L L(t)] + I_D \dot{D}(t) + I_F \dot{F}(t) + I_G \dot{G}(t) \quad (25)$$

The solution is obtained by solving the system:

$$\frac{\mathcal{H}}{\mathcal{H}_S} = e^{-rt} [P_M m_S - W_L l_S] + I_D d_S + I_F f_S + I_G g_S = 0 \quad (26)$$

$$\frac{\mathcal{H}}{\mathcal{H}_N} = e^{-rt} [P_M m_N - W_N - W_L l_N] + I_D d_N + I_F f_N + I_G g_N = 0 \quad (27)$$

$$\frac{\mathcal{H}}{\mathcal{H}_D} = -\dot{I}_D \quad (28)$$

$$\frac{\mathcal{H}}{\mathcal{H}_F} = -\dot{I}_F \quad (29)$$

$$\frac{\mathcal{H}}{\mathcal{H}_G} = -\dot{I}_G \quad (30)$$

$$\frac{\mathcal{H}}{\mathcal{H}_D} = d(D, G, R) \quad (31)$$

$$\frac{\mathcal{H}}{\mathcal{H}_F} = f(F, N, G) \quad (32)$$

$$\frac{\mathcal{H}}{\mathcal{H}_G} = g(G, S, N, D, R) \quad (33)$$

$$I_D(T) \geq 0, D(T) \geq 0, (D(T) - D_0) I_D = 0 \quad (34)$$

$$I_F(T) \geq 0, F(T) \geq 0, (F(T) - F_0) I_F = 0 \quad (35)$$

$$I_G(T) = 0 \quad (36)$$

To understand the effects of prices and policy instruments on the stock of resources (D and F) and profitability of the system, it is necessary to describe the relationships between the biophysical variables in equations (16) to (18).

Soil Depth

Existing soil depth is expected to have either no effect on soil formation and loss, or to have a positive effect, for convenience (and following McConnell, 1983) it can be safely assumed that $d_D = 0$. Pasture cover is expected to decrease the rate of soil erosion by protecting soil from runoff, therefore $d_G > 0$. Rainfall is expected to have a negative effect on soil depth $d_R < 0$ in the case of large rainfall events which cause soil runoff, or no effect ($d_R = 0$) for normal rainfall events which cause no soil loss.

Soil Fertility

In general, there is no reason to expect that current soil fertility should affect its own rate of change, except when pasture cover prevents leaching of applied fertiliser; since the effect of pasture cover is directly included in equation (17), it can be safely assumed that $f_F = 0$. Fertiliser application increases soil fertility, therefore $f_N > 0$. Pasture cover is related to the growth rate of grass, which uses soil nutrients, increasing pasture cover, however, may also increase the amount of nutrients that are retained in the soil rather than lost to runoff or leaching; therefore $f_G > 0$ or $f_G < 0$ depending on the circumstances. To avoid this ambiguity, the function can be improved by separating nutrient retention by the soil from nutrient use by the pasture.

Pasture Growth

Pasture acts as an intermediary between soils and animals and it has an effect on the rate of resource use. The rate at which the natural capital, represented by soils, shrinks or grows is considerably affected by pasture cover. The function $G(t)$, which has been well studied for many pasture species, is sigmoid in shape (Cacho, 1993), which implies that $\dot{G}(t)$ is concave in G with a maximum at some value $0 \leq \bar{G} < \infty$ which, in turn, implies that $g_G \geq 0$ or $g_G \leq 0$ depending on the current pasture mass. Animals consume pasture, thus $g_S < 0$, and $g_{SS} < 0$ because large numbers of animals will have an additional negative effect on pasture through trampling. Finally g_N, g_D and $g_R > 0$ because soil fertility, soil depth and rainfall increase pasture growth rate.

Model Solution

The comparative dynamics of this problem are quite complex and their analytical derivation will not be attempted. The differential equations (16) to (18) are nonlinear, they could be conveniently represented by biophysical models of soil, plant and animal dynamics. Numerical solution of the problem could then be used to gain insight into the dynamics of the optimisation model (15)-(23). Development of a numerical model is a subject for future research. The effects of externalities, discount rates and uncertainty are discussed in the remainder of this paper.

Externalities

The role of externalities and the need to measure them in order to reflect the social costs of economic activity and resource use should be an essential component of any attempt to design sustainable agricultural systems. Externality costs are easier to measure at a national scale, because the information is more readily available. Templet (1995) presents an empirical analysis of externalities at the State level in the U.S., he measures the subsidies created by externalising pollution, energy and tax costs, and finds that failure to spend on pollution control is positively related to poverty, income disparity and unemployment. He concludes that pollution spending might be progressive, rather than regressive (as suggested by Baumol and Oates, 1988). Based on these findings, Templet's recommendations include (i) that states set environmental standards based on the assimilative capacity of the environment; (ii) that a combination of direct controls and economic incentives be used to maintain a threshold level of discharges (using instruments such as emission taxes, tradable permits and tax exemptions on environmental compliance); (iii) that emission taxes should at least equal the pollution subsidies calculated in the paper; and (iv) that the functions of economic development agencies and environmental quality agencies be combined, or linked, to ensure consistent policies. Although one may disagree with the techniques (linear regression) or the conclusions reached by Templet, his paper raises relevant questions which can be carried to the local level.

In order to design policies that encourage sustainability and eliminate (or internalise the costs of) externalities, government agencies need to be able to measure these costs. At the local level, the physical quantities associated with externalities can be estimated through modelling; variables such as soil erosion, fertiliser leaching and pesticide drift can be simulated for given environmental conditions and resource levels. The model presented above can be extended to account for the externalities associated with the fertiliser input and the meat output, through the effects of stocking rate and pasture cover on soil depth and fertility losses; assigning monetary values to these losses, however, is not a trivial matter.

Steiner et al. (1995) present an excellent discussion of the measurement of externalities in agriculture and most of the discussion that follows is based on their paper.

Fertiliser Externalities

Fertiliser externalities may arise from either the application of excessive amounts of fertiliser or wrong timing in its application. Fertiliser applied which is not captured by the soil may be carried away and affect streams, lakes, urban drinking supplies and water tables. In Australia, the incidence of blue-green algae blooms, which contaminate drinking water supplies, is a costly problem caused by excessive nutrients in waterways. Steiner et al. (1995) classify the cost of fertiliser externalities into (i) regulatory costs, whose measurement is complicated by the fact that fertiliser and pesticides are often found together; (ii) health costs, caused primarily from exposure to nitrates; and (iii) environmental costs, which include eutrophication, water turbidity, oxygen depletion, loss of marine life, and loss of recreational benefits.

Measuring fertiliser externalities at the catchment level is complicated by the distinction between point and non-point sources. This problem does not arise in the context of a biophysical model where mass balances are maintained to account for the fate of nutrients to various destinations. The physical amount of fertiliser lost to the system (E) over a given period of time can be described as:

$$\dot{E}(t) = e(N(t), G(t), R(t)) \quad (37)$$

Fertiliser applied (N) is either incorporated into the soil and accounted for by equation (17), or lost from the system and accounted for in equation (37). The actual cost of e will depend on the location of the farm and the fate of the lost nutrients.

Soil Externalities

Soil loss represents a direct cost caused by decreasing yields, this effect is captured by equations (16) and (18), an additional cost may occur in the form of loss of land value, which can be accounted for by adding a terminal value to the land in (15). Soil externalities (off-site effects of soil erosion) may arise when soil is carried into streams, causing siltation and other problems. Physical estimates of soil runoff can be made using the universal soil loss equation (Steiner et al., 1995) which could be incorporated into equation (16). Given the physical erosion rates the off-site damage can then be estimated by multiplying by the damage estimate (\$/ton) for the region. The United States Department of Agriculture (USDA) has developed a set of categories to classify the off-site effects of soil loss, these include: recreation, water storage, navigation, flooding, roadside and irrigation, commercial fishing, municipal water treatment, municipal and industrial use and steam power cooling. The total damage caused by soil erosion in the U.S. was estimated at over US \$10 billion in 1989 (Steiner et al., 1995).

Pesticide and Chemical Externalities

The external costs of pesticide and agricultural chemicals can be considerable. These include regulatory costs, chemical control costs, water pollution, human health and environmental costs (such as increased pest resistance and damage to fish and wildlife populations). Although the model presented here is not designed to account for these costs, the use of chemicals could be included by extending the definition of the production function (14) and the pasture growth function (18) to account for the effects of chemical use.

Salinity

Dryland salinity is an important environmental problem in some regions of Australia. The incidence of dryland salinity is related to water table dynamics and is strongly affected by land-use patterns. Certain crops and agricultural practices tend to increase salinity, while trees, some pasture species and deep-rooted crops tend to decrease it. Direct measurement of sources of salinity at the catchment level is difficult, because of the complexity of water table dynamics. Once again, modelling may help in this regard, detailed models of water table dynamics exist and can be incorporated into optimisation models. The inclusion of salinity effects into our model would require an additional state variable, with its corresponding equation of motion, which could be based on a physical water balance model.

Uncertainty, Stability and Resilience

Up to this point the discussion has been based on a deterministic model, which is useful to identify relevant variables and understand the system being studied. However, the fact that the environment is stochastic cannot be ignored, particularly when dealing with long term models. In an uncertain world, attributes such as stability and resilience may take precedence over profits. Holling (1986) defines stability as *the propensity of a system*

to attain or retain an equilibrium condition, either as a steady state or a stable oscillation, a stable system tends to return rapidly to its equilibrium position when perturbed and it exhibits low variability and resistance to change. Resilience, on the other hand, refers to the ability of a system to maintain its structure and pattern of behaviour in the face of disturbance (Holling, 1986); a resilient system may exhibit high variability and must be able to adapt to change.

Holling points out that reduced variability achieved through management is likely to lead to smaller stability regions. He provides examples of policies that reduced the probability of socially or economically undesirable events (such as control of forest fires) and argues that, although these policies may be successful in their immediate objectives, they also may produce a system with lower resilience (as an example consider the devastating forest fires caused by decades of fire control which allow the accumulation of large amounts of fuel in the forest floor). The importance of resilience is also discussed by Chavas (1993), who uses a dynamic model to analyse irreversibility and the ability of a system to react to unexpected shocks. He derives an *adaptive value* and stresses the value of strategies which avoid the irreversibility of extinction (from either a firm or a species standpoint). He argues that "many behavioral decisions involved in sustainability issues may not be outcomes of an optimizing process" and concludes that empirical analysis of sustainability and resource policy should not rely exclusively on the assumption of optimising behaviour because, even in the absence of optimising behaviour, adaptive strategies can improve the resilience of a system. Chavas states that "the explicit incorporation of this adaptive value in economic analysis appears to be a crucial step in the evaluation of sustainability issues.

The Role of Discounting

The optimal trajectories produced by dynamic models, and the rate at which resources are exhausted, tend to be highly sensitive to the discount rate used. The need to include sustainability constraints (21) and (22) in the grazing model, arises from this sensitivity. The alternative of attaching a terminal value to the resources (D and F), would generally have negligible effect for long planning horizons. Through numerical modelling it should be possible to find terminal resource values that encourage sustainability for given discount rates.

Norgaard and Howarth (1991) argue that, when dealing with sustainability, decisions over time have not been properly treated by economists, who have failed to distinguish between the efficient use of this generation's resources and reassignment of resources to the next generation. They present a simple model that accounts for this transfer, their concept may offer interesting possibilities to modify the standard dynamic economic model.

Conclusions

The understanding and measurement of sustainability and externalities are in their infancy, there is much work to be done by economists and other scientists. The model presented in this paper provides a formal framework through which biophysical and economic information can be integrated. The model can be used as a base to design numerical models which can help us understand the long-term implications of alternative policy scenarios and determine future research directions.

References

- Barnett, V., Payne, R. and Steiner, R. (1995). *Agricultural sustainability. Economic, environmental and statistical considerations.* John Wiley and Sons, Chichester.
- Baumol, W.J. and Oates, W.E. (1988). *The theory of environmental policy.* Cambridge University Press, Cambridge.
- Cacho, O.J. (1993). A practical equation for pasture growth under grazing. *Grass and Forage Science*, 48, 387-394.
- Cacho, O.J. (1995). Simulation models and sustainability of grazing systems. In Binning, P, H. Bridgman and B. Williams, MODSIM 95, International Congress on Modelling and Simulation, Proceedings, Modelling and Simulation Society of Australia, 1:28-32
- Cai, Y.L. and Smith, B. (1994). Sustainability in agriculture - a general review. *Agriculture, Ecosystems and Environment*, 49, 299-307.
- Chavas, J.P. (1993). On sustainability and the economics of survival. *American Journal of Agricultural Economics*. 75:72-83.
- Conway, G.R. and Barbier, E.B. (1988). After the green revolution: Sustainable and equitable agricultural development. *Futures* (Dec):651-70.

- Dalsgaard, J.P.T., Lightfoot, C. and Christensen, V. (1995). Towards quantification of ecological sustainability in farming systems analysis. *Ecological Engineering*, 4, 181-189.
- de Wit, J., Oldenbroek, J.K., van Keulen, H. and Zwart, D. (1995). Criteria for sustainable livestock production: a proposal for implementation. *Agriculture, Ecosystems and Environment*, 53, 219-229.
- Gale, R.P. and Cordray, S.M. (1994). Making sense of sustainability - 9 answers to what should be sustained. *Rural Sociology*, 59, 311-332.
- Herdt, R.W. and Steiner, R.A. (1995). Agricultural sustainability: concepts and conundrums. In Barnett, V., Payne, R. and Steiner, R. (ed) *Agricultural sustainability. Economic, environmental and statistical considerations*. John Wiley and Sons, Chichester. 3-13.
- Holling, C.S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. In Clark, W.C. and Munn, R.E. (ed.) *Sustainable development of the biosphere*. Cambridge University Press, Cambridge, 292-317.
- McConnell, K.E. (1983) An economic model of soil conservation. *American Journal of Agricultural Economics*. 65:83-89.
- Norgaard, R.B and Howarth, R.B. (1991). Sustainability and discounting the future. In Costanza, R. *Ecological Economics*, Columbia University Press, New York. 88-101.
- Pandey, S. and Hardaker, J.B. (1995). The role of modelling in the quest for sustainable farming systems. *Agricultural Systems* 47:439-450.
- Pearce, D., Barbier, E. and Markandya, A. (1990). *Sustainable development*. Edward Elgar Publishing Ltd., Aldershot.
- Ruttan, V.W. (1994). Constraints in the design of sustainable systems of agricultural production. *Ecological Economics*, 10, 209-219.
- Steiner, R.A., McLaughlin, L., Faeth, P. and Janke, R.R. (1995) Incorporating externality costs into productivity measures: A case study using US agriculture. In Barnett, V., Payne, R. and Steiner, R. (ed) *Agricultural sustainability. Economic, environmental and statistical considerations*. John Wiley and Sons, Chichester. 209-230.
- Templet, P.A. (1995). Grazing the commons: an empirical analysis of externalities, subsidies and sustainability. *Ecological Economics*, 12:141-159