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THE SUPPLY OF NON-DEGRADED AGRICULTURAL LAND*

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Profitability increases because of favourable product or factor price changes provide incentives for profit-maximising farmers, who use soils in conjunction with other cooperant inputs, to increase their investment in the preservation of soil-quality, whenever there exist economically viable technologies for preserving soils. However, when such technologies do not exist, regardless of whether farmers utilise soils as non-renewable or renewable resources, such profitability increases are associated with a long-run deterioration in soil quality.

1. *Introduction*

In this paper the relation between factor and product prices, farmer land conservation investment decisions and observed levels of land degradation is examined. A conventional wisdom believed strongly by many in the agricultural economics profession is that when product prices rise, or farmers benefit from subsidies directed towards inputs, agricultural land will tend to be used *more* intensively, leading to lower equilibrium land quality or, equivalently, to more degraded land. In particular, in the U.S. it has been argued by many descriptive agricultural economists that agricultural price-supports have exacerbated soil erosion — hence environmental arguments have come to be advanced alongside standard economic efficiency arguments for the elimination of such supports: see, for example, Bunce (1942), Ciracy-Wantrup (1952) and a number of the papers in Phipps *et al.* (1986).[1]

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[1] There is also considerable literature arguing the opposite view. Schuh (1987) argues that price disincentives, such as export taxes and high marketing costs, lead farmers to *undervalue* land and hence to degrade it more than they otherwise would. More generally, economic development and technical progress are seen as creating abundance rather than scarcity (for example wheat prices are currently about half what they were in real terms 125 years ago) thereby *reducing* demands for natural resources such as land and thus providing long-term incentives for their degradation.

Recently, an attempt has been made by LaFrance (1989), (1990) using dynamic duality arguments, to justify rigorously the view that the supply of non-degraded land will decrease with favourable price changes. This view was criticized by Clarke (1991). LaFrance (1991) then argued that land quality and price are not *always* negatively related but maintained that the type of negative relationship hypothesised is 'generic'. (Also, see La France, this journal.)

These types of arguments have wider implications than simply the analysis of price-supports. They suggest that, for example, if a decentralised competitive economy does lose productive land due to degradation then, without input substitution, the consequent reduction in agricultural supply will boost product prices and will provide incentives for increased future land degradation. They also suggest that product price increases, due to population-induced growth in demand will, in the absence of offsetting input substitution, lead to worsening future land degradation problems. Market processes would thus operate in a Malthusian fashion and be unstable since they would *not* operate to 'correct' past degradation mistakes — rather they would intensify and worsen them.

There are a number of possible intuitive rationales for such a viewpoint in an economy with privately-owned land and no off-site external environmental effects. First, it might be argued that favourable price changes will encourage farmers to utilise increasingly marginal lands which are more susceptible to environmental damage. Second, it could be suggested that soils are overwhelmingly a non-renewable resource which should optimally be mined until they are exhausted. These arguments are discussed below in Section 4 and the conclusion is drawn that they are only partially convincing. Whatever their value, these types of arguments are *not* necessary to support the hypothesised negative relation between soil quality and prices. A third rationale that often underlies analysis of the issue is the view that farmers face upward-sloping individual supply curves and perfectly elastic demands. Then higher product prices call for more output via a shift along the supply schedule while lower factor prices lead to shifts outwards in the supply curve and, again, increased output. In both cases the increase in supply is presumed to impose greater pressure on the use of farm soils and hence to increased equilibrium land degradation.

This type of rationale is untenable, in general, because supply and land-use decisions by rational farmers will not be taken independently of soil conservation measures and their associated costs. As pointed out by McConnell (1983), Kirby and Blyth (1987), (and many others), the farmer in this situation faces an intertemporal choice regarding the use of her/his farm. Supply decisions will not therefore be related to *current* output prices independently of land-investment decisions.

The simplest way to see this is to ignore factor substitution altogether and to suppose that, at time $t = 0$, a farmer has available a single discrete soil-conservation investment option which will increase the cumulative discounted value of output over an unending time horizon. The value of this increased output is:

$$R = \int_0^\infty P(t)\Delta y(t)e^{-\delta t}dt$$

where δ is the farmer's discount rate, $P(t)$ is expected product price and $\Delta y(t)$ is the expected change in output at future time t (this may be negative for a sufficiently small t but, by hypothesis, the value of the integral as a whole must be positive).

The present value of the costs associated with this soil-conservation program is:

$$C \equiv \int_0^\infty c(t)e^{-\delta t}dt$$

where $c(t)$ is the instantaneous anticipated conservation cost at t.

Applying standard cost-benefit analysis, the farmer will proceed with this soil conservation project provided R-C is positive. Obviously this decision (and the consequent *future* output time path) depends on current and future output prices. Also obviously, the project is more likely to be accepted the greater are product prices $P(t)$ or the lower are conservation costs $c(t)$ (now or at any time in the future). Thus, in this simple setting, ignoring the effects of price stimuli in providing incentives for the use of inputs (e.g. fertiliser, pesticide, irrigation) which may deplete soil quality, favourable product price movements (and, in so far as they reduce conservation costs, favourable factor price movements) will increase the incentive to protect land capital and hence imply improved (rather than more degraded) levels of soil quality. Thus, under these conditions, the supply of non-degraded land will *not be* negatively related to prices.

Admittedly this is an oversimplified view of the land conservation investment decision since it posits only a discrete improvement technology and ignores all possibilities for factor substitution. The aim in the following analysis is to generalise this simplistic analysis into a more realistic setting. Thus the aim is to consider the implications of product and factor price changes for agricultural land degradation when factor substitution and a spectrum of conservation technologies are possible.

The general plot of this analysis is simple and can be set out in advance. Present-value-maximising farmers (with foresight) who can utilise viable technologies (with cooperant inputs) to offset the effects of land degradation are shown to respond to favourable price movements by increasing their sustained investment in soil quality thereby reducing the extent of long-run land degradation. When, however, farmers do not possess viable soil conservation technologies and mine soils as a non-renewable resource, either type of favourable price movement (e.g. subsidy) leads to a lower equilibrium level of soil quality. In this latter case the equilibrium level occurs when soils are abandoned.

Unlike Clarke (1991), in the current analysis consideration is given to the role of soil-regeneration which may even occur independently of current output and the current state of soils. Provided such regeneration occurs in a setting where profitable auxiliary soil-conservation technologies do not exist (this scenario captures the main features of the seminal McConnell (1983) model of soil conservation), then again the finding is that soil conservation and price are negatively related *even though* soils are never abandoned.

While these conclusions are established in a stylised setting where only soil quality and some other variable input are productive, the situation where an arbitrary number of variable inputs are used is also discussed.

It is important to stress at the outset that in this analysis the focus is mainly on on-site land degradation issues — external off-site effects are ignored although, as we note in Section 6, the results have implications for the latter. The property right (bad tenant) issues which bring about degradation in a setting where land is leased rather than owned are also not considered. Thus major practically-important sources of land degradation in Australia (and elsewhere) are excluded. The first-best ways of dealing with such problems inevitably involve Pigovian taxes or Coasean bargaining and either property right or leasing-system reforms. If these prerequisites for allocative efficiency are implemented, the more specific cases that are considered here become more interesting.

2. *The Model*

In what follows, *degraded land* is defined to be land with diminished agricultural and/or biological productivity. Typically such land is associated with impoverished and eroded soils, low levels of vegetation, low levels of water usage due to excessive runoff and low genetic diversity. Note the two criteria here for the assessment of soils: on the one hand the valuation is utilitarian, with soils viewed as productive agricultural assets with which site biomass values are being optimised in economic terms. The other valuation is biological (and perhaps aesthetic), emphasising attributes which are intrinsically valuable such as environmental authenticity and biodiversity.

For simplicity, suppose agricultural attributes can be indexed by a single indicator of 'soil quality', Q, with smaller values of this variable indicating more degraded land in the sense of lower agricultural productivity.[2] Also suppose perfect markets exist for the utilitarian attributes while biological attributes are, at least, partially unmarketed

[2] Obviously, increasing the agricultural productivity of soils need not enhance biological valuation. Thus, draining wetlands may substantially enhance agricultural productivity but reduce biodiversity.

(for example because of a lack of property rights on genetic resources) so that soil-owners are led to undervalue soils because of their inability to appropriate what we term *on-site externalities*, namely the biological and aesthetic benefits that accrue to society from the unmarketed biological attributes. These are on-site externalities because they stem from the state of land itself as opposed to *off-site externalities* which relate to the effects of one agricultural producer's activities on the costs of another. Even in the absence of such off-site externalities we suppose there is concern over the underprovision of attributes such as biodiversity by markets.

In this type of setting then is modelled the behaviour of a price-taking farmer who has purchased (freehold) land of given area with uniform level of quality Q (e.g. soil depth, percentage of organic matter in soil, chemical fertility, lime content etc.), and who then combines this land with some variable input X to produce a crop in quantity Y where:

(1) $$Y = F\,[Q,X]$$

where F is a strict concave production function with $F_1 > 0, F_2 > 0, F_{11} < 0$ and $F_{11}\,F_{22} - F_{12}^2 > 0$. Diminishing returns here could stem from the existence of a fixed factor (e.g. farm management) as well as decreasing possibilities for investment in profitable soil conservation. Labelling the second input 'land' is entirely inessential — it could in fact be *any* second input (such as fertiliser) in which case (1) describes maximum feasible output on a *given* land area with the one variable input (fertiliser) and one quasi-fixed input (capital invested in soil quality).

For simplicity however the role of inputs in addition to the two cited is initially suppressed. This enables the analysis to concentrate on the role of the single variable input and land quality. Note that the effect of improved soil quality on the marginal product of the variable input is

(2) $$\frac{\partial}{\partial Q}\left[\frac{\partial F}{\partial X}\right] = F_{12} \gtrless 0.$$

This quantity is positive if the variable input and soil quality inputs are cooperant (i.e. Edgeworth complements) and negative if they are substitutes. While complementarity in the sequel is sometimes hypothesised it is important to understand that the specification of technology does not *inevitably* imply this is the case: thus increasing certain types of fertiliser input might reduce the marginal product of investment in soil quality in which case the respective inputs would be Edgeworth substitutes.

Note also that (unlike McConnell (1983)) the *flow* effects of reduced soil quality (e.g. soil losses) on *current* output are ignored. Only the relevant *stock* effects are considered. Soil losses in this formulation reduce soil quality and, by this means alone, impact on production possibilities — they do not have a role as an input in determining current output. There are at least two reasons why this modification to standard modelling approaches is acceptable. First, as mentioned, the flow effects of output (or cropping) intensity in reducing soil quality *are* accounted for via the soil quality adjustment dynamics. This seems a reasonable way of accounting for such flow effects since soil losses accompanying *current* output will be a consequence of, rather than a determinant of, current yields.[3] These losses have their important cumulative effects via stock effects on *current* yields. This is the view taken by Walker (1982), Walker and Young (1986) and van Vuuren (1986) who use *soil depth* (rather than the rate of topsoil loss) as a surrogate for soil conservation in their specification of agricultural production functions. Second, most of the subsequent comparative static analysis is implemented in terms of a steady state where net changes to soil quality are zero so that including such net changes as an argument in the farmer's production function will have no effect on our results.[4]

Soil quality at time t, $Q(t)$, is supposed to evolve in response to three classes of factors. First, investments $I(t) \geq 0$ in soil quality promote flow improvements in quality at the rate $\alpha I(t)$, $\alpha > 0$. $I(t)$ can be thought of as being defined in physical terms as the instantaneous application of, for example, fertiliser or lime to soils, the application of drainage or leaching technology, the use of contour cultivation etc. Second, suppose that in the absence of soil quality investments, soil quality itself will regenerate/deteriorate at the constant exponential rate $\beta Q(t)$, $\beta \gtrless 0$: in particular allowance is made for the possibility that a non-sustained investment program will tend to dissipate exponentially through time. Finally, assume that soil quality will be depleted in proportion to the current intensity of production as measured by output. Thus production at rate F depletes soils at rates γF where $\gamma \geq 0$. The soil quality dynamics are then represented as:

$$\dot{Q}(t) = \alpha I(t) = \alpha I(t) - \beta Q(t) - \gamma F\,[Q(t), X(t)\,] \qquad (4)$$
$$Q(0) = Q_0$$

where the dot indicates the time derivative d/dt. For convenience the time variable is often suppressed in what follows:[5]

[3] The reason for McConnell's (1983) inclusion of soil losses as a production function argument seems hard to isolate. It cannot reflect 'adjustment cost' considerations since (in the McConnell formulation) higher rates of soil loss are associated with *increased* output.

[4] Of course the presence of such flow impacts on current output might make our emphasis on steady state properties less convincing. On the other hand the analysis of transitional dynamics with such flow effects makes for a highly intractable analysis: see, for example, LaFrance (1991).

[5] None of the long-run results derived in this paper depends on the linear specifications of equation (4). They do however depend on the assumption of separability in each of the variables $I(t)$, $Q(t)$ and F. Essentially the same long-run results obtain if (4) is replaced by $\dot{Q}(t) = A(I(t)) - B(Q(t)) - C(F(t))$ where A is an increasing concave function

cont.

This formulation might seem unconventional since the control $I(t)$ is the rate of investment in soil conservation rather than (for example) the rate of soil loss (as in McConnell (1983)). This is an unimportant distinction however since $I(t)$ *determines* the net rate of soil loss $\dot{Q}(t)$. Note also that (4) does permit the analysis of *intensification effects*[6] — increases in prices will increase the incentive to produce more output but at the expense of increased soil degradation. Most importantly, (4) does not (as in McConnell (1983)) include a small positive constant term reflecting the slow natural regeneration of soils — whether or not this term is included has no bearing on the results of this part of the analysis but does effect the analysis of situations where economically feasible technologies for offsetting the impact of degradation do not exist. In Section 4 below, these considerations are discussed further in terms of a modified McConnell model. At this stage the *only* way soil quality is allowed to be enhanced is by *investing* in it.

Given this structure the farmer selects time paths for investment in soil quality and the variable input to maximise the discounted value of profits received over an unending time horizon[7] i.e.:

$$\max_{I(t),\,X(t)} \int_0^\infty e^{-\delta t}\{PF[Q,X] - qI - aX\}\,dt \qquad]T.$$

subject to equation (4) where

δ = positive constant discount rate,

P = constant output price,

q = constant price of soil quality investment,

a = unit cost of the variable input.

The task of solving problem T is an optimal control problem. The relevant current-value Hamiltonian is:

. . . *cont.*

of I, B is a U-shaped convex function of Q and C is an arbitrary increasing function of F. In fact the results for this case can be derived from what follows by setting $\alpha = A'$, $\beta = B'$ and $\gamma = C'$ where the prime indicates derivative. The increased generality obtained with this extension does not add anything to the results and hence is not pursued.

[6] By 'intensification' we mean the incentive to produce more in response to increased price. In agricultural economics the term is conventionally used more generally to refer to an increased use of all variable inputs (fertilisers, pesticides) on given land.

[7] Agricultural economists (such as McConnell (1983)) seem loathe to consider farmers as optimisers with infinite foresight and prefer instead to maximise discounted returns over a finite horizon together with the present value of the farm at the end of the horizon. In so far as resale value accurately reflects the discounted stream of future returns given the inherited soil quality prevailing at that time (the empirical evidence by King and Sinden (1989) that we discuss subsequently strongly suggests it does) then such finite horizon optimisation is equivalent to infinite horizon optimisation.

(5) $$H = PF[Q,X] - qI - aX + \Psi(\alpha I - \beta Q - \gamma F[Q,X])$$

where Ψ is a continuous shadow price (costate variable).

Necessary conditions for an interior optimum require:

$$\partial H/X = 0$$

(6) $$\Rightarrow \; F_2[Q,X](P - \gamma\Psi_2) - a = 0$$

$$\partial H/\partial I = 0$$

(7) $$\Rightarrow \; \Psi = \theta/\alpha$$

$$\dot{\Psi} = \delta\Psi - \partial H/\partial Q$$

(8) $$\Rightarrow \; \dot{\Psi} = \Psi(\delta + \beta + \gamma F_1[Q,X]) - PF_1[Q,X].$$

Since the Hamiltonian is linear in the rate of soil-improving investment the adjustment dynamics for such investments take a very specific form. In fact, soil quality is driven to its long-run desired level either through a program of zero investment in soil quality (this is the case where initial soil quality is too high) or through a pulse investment in soil quality (when initially soil quality is too low). Thus the optimal control problem is *singular* in the level of soil quality investment.

This characterisation of soil quality conservation programs is related to existing views of the land degradation process. Bunce's (1942) model suggested that, while the net returns to farmers from soil conservation remain constant through time, the returns without conservation would decline. Thus, in Figure 1, conservation should be initiated at time T after an initial phase $(0, T)$ where soil quality is progressively degraded through a program of zero investment in conservation.[8] Walker (1982), on the other hand, considers soils with low initial depth and showed (as in Figure 2) that soil conservation investment should commence immediately. With feasibility side-constraints added to prevent pulse-output and pulse-investment responses, the most-rapid-approach dynamics of our analytical model are essentially the same as the dynamics described in the works of these early authors. Moreover, once conservation investment is initiated in each framework it is sustained indefinitely.

Suppose for the moment that the long-run desired level of soil quality in our framework is interior so it is non-optimal to simply mine the soil as an exhaustible resource until its productive potential is exhausted. This is a reasonable assumption if optimal farming plans clearly call for an on-going farming operation. The formal conditions for this to be true are discussed below.

With the assumption of a positive long-run level of optimal soil quality it is straightforward to examine the long-run sensitivity proper-

[8] Seitz *et al.* (1979) estimated that, depending on discount rates, this phase might last from 40 - 60 years.

FIGURE 1
Net Returns and Conservation. The Bunce Case of High Initial Soil Fertility

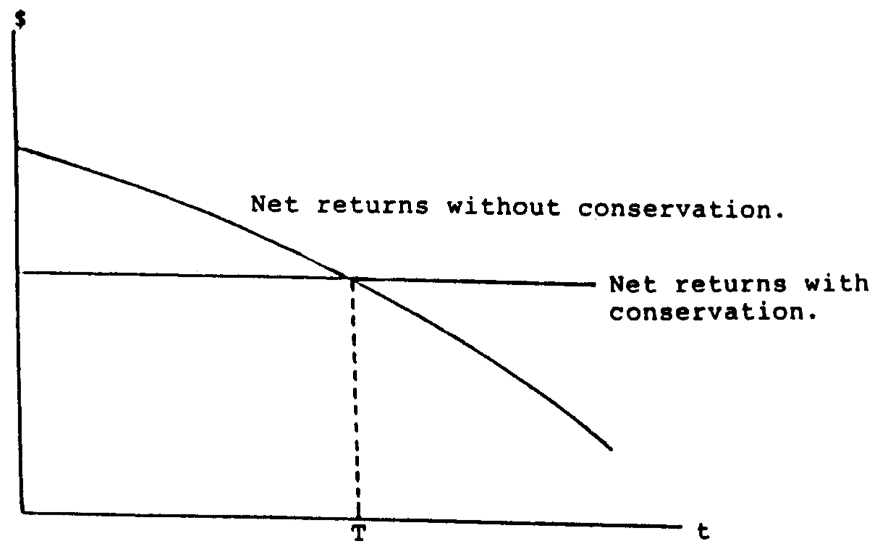
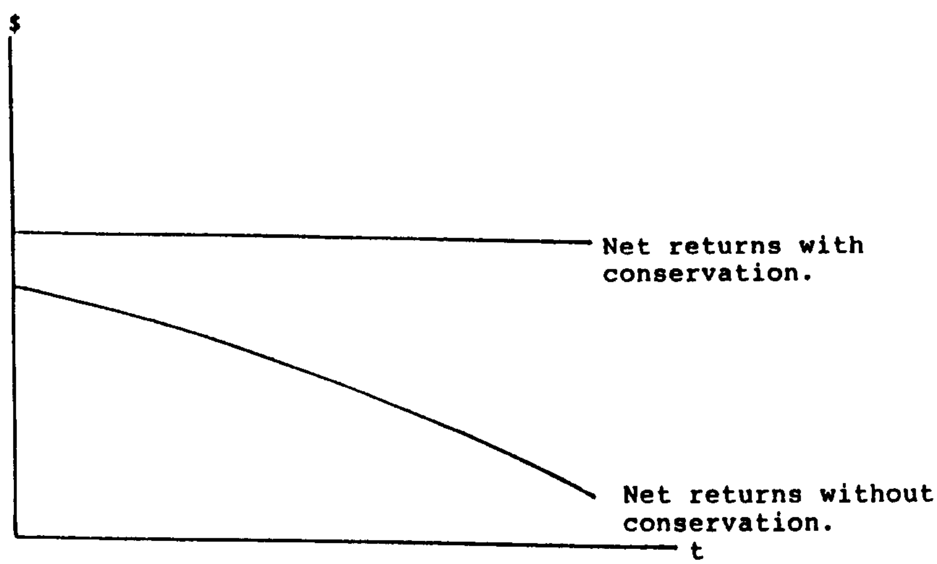


FIGURE 2
Net Returns and Conservation. The Walker Case of Low Initial Soil Fertility



ties of the farmer's production plans. In such an equilibrium (7) must hold so, since q and α are parameters, then $\dot{\Psi} = 0$. Thus from (8):

$$q(\delta + \beta + \gamma F_1[Q, X]) - \alpha P F_1[Q,X] = 0 \tag{9}$$

Furthermore from (6) it follows that:

$$F_2[Q, X](P - \gamma q/\alpha) = a. \tag{10}$$

Equations (9) and (10) define the long-run optimal values of the marginal products of land quality and the variable input respectively. These equations determine the steady state optimal values of Q and X given the parameters α, β,γ, δ, q, a and P. For convenience define:

$$E = P - q\gamma/\alpha$$

so the Jacobian determinant of (9), (10) is:

$$\Delta = \begin{vmatrix} -\alpha E F_{11} & -\alpha E F_{12} \\ E F_{21} & E F_{22} \end{vmatrix} = \alpha E^2 (F_{12}^2 - F_{11} F_{22}). \tag{11}$$

It is straightforward to see that the sufficiency conditions for Q and X to maximise the Hamiltonian H in the steady state (itself a necessary condition for optimality) require:[9]

$$E > 0 \tag{12}$$

and

$$\Delta < 0. \tag{13}$$

These results enable the analysis of the long-run comparative static properties of the equilibrium defined by (9) and (10). Condition (12) implies that the equilibrium marginal products of land quality and the variable input, defined by equations (9) and (10), are positive. In fact (12) is also a necessary condition for the optimal control problem T to converge to a non-zero level of land quality i.e. for an interior equilibrium (a feasible conservation technology) to prevail. However (12) alone is *not* sufficient. This is simplest to see in the particular case where the variable input is fixed at some predetermined level $X = \bar{X}$. Then the steady state optimal level of land quality is defined by (9) alone, namely:

$$\delta + \beta = (\frac{aP}{q} - \gamma)\, F_1[Q,X]$$

[9] The steady state Hamiltonian is defined by

$$H = PF[Q,A] - aA - q\beta Q/\alpha - q\gamma F[Q,A]/\alpha.$$

The sufficiency conditions for Q and A to maximize H are that the Hessian matrix

$$\begin{bmatrix} \partial^2 H/\partial Q^2 & \partial^2 H/\partial Q \partial A \\ \partial^2 H/\partial Q \partial A & \partial^2 H/\partial A^2 \end{bmatrix} = \begin{bmatrix} F_{11}E & F_{12}E \\ F_{12}E & F_{22}E \end{bmatrix}$$

be negative definite which can be easily seen to require both $E > 0$ and $\Delta < 0$.

If the marginal product of soil quality investment remains bounded then this equation will only have a solution if δ and β are not too large. In words: *provided the discount rate and the rate at which soil quality dissipates in effectiveness are not too large there will exist an interior equilibrium level of soil conservation investment.* This is the crucial condition determining the viability of an equilibrium conservation plan. For large values of these parameters (when this condition is not met) it will be optimal to exhaust the potential of soils by depleting their quality cumulatively through time. This is discussed further in Section 3.

The long-run comparative static properties of the equilibrium are summarised in Table 1, assuming that (12) and (13) hold.

For definiteness the results in Table 1 are calculated (and discussed) for the empirically important case where the inputs are Edgeworth complements (so $F_{12} > 0$). An objection to this might be that the hypothesis of substitutability may be more reasonable since, taking the variable input to be homogenous land, large farms are often characterised by soils of low fertility while small farms have better soils. This is incorrect in terms of the definition of substitutability adopted here (i.e. cross-effect on marginal products) since, even on a very large farm, the marginal product of an additional hectare should not be reduced by an investment in improved soil quality (this would be implied by the substitutability hypothesis). The case of Edgeworth substitutes is discussed briefly at the end of Section 3.

Finally, the case where the variable input is fixed or where soil quality is the main output determinant can be determined by setting $F_2 = 0$ in Table 1.

3. *Comparative Statics*

Product price effects

An increase in effective product prices, perhaps as the result of an output subsidy, has the effect of increasing the farmer's use of the variable input and of increasing the aggregate investment in soil quality. If, the variable input is fixed in advance, then from (9):

$$\frac{dQ}{dP} = \frac{-F_1}{F_{11}E} > 0$$

so soil quality is always improved.

These results are intuitive in the sense of being consistent with the standard analysis of a profit-maximising firm and would scarcely require discussion were it not for contrary claims. In simple terms, an increase in product prices raises the value of the marginal product of any input cooperant with soil quality and likewise increases the value of the marginal product of investment in soil quality. Hence the farmer has the incentive to use more of the cooperant input and to take increased care in maintaining soil quality. Output price subsidies, in this event, will thus lead to *less* long-run land degradation rather than more as claimed by LaFrance (1990).

TABLE 1
Long-Run Analysis of Farmer Choice of Soil Quality and Input Use

1. Product Price Effects (P)

$$\frac{dQ}{dP} = \frac{\alpha E(F_1 F_{22} - F_{12} F_2)}{\Delta} > 0 \quad \frac{dX}{dP} = \frac{\alpha E(F_{11} F_2 - F_{21} F_1)}{\Delta} > 0$$

2. Capital Cost Effects (q)

$$\frac{dQ}{dq} = \frac{E(\gamma F_2 F_{12} - (\delta+\beta+\gamma F_1)F_{22})}{\Delta} < 0 \quad \frac{dX}{dq} = \frac{E[(\delta+\beta+\gamma F_1)F_{21} - \alpha\gamma F_2 F_{11}]}{\Delta} < 0.$$

3. Variable Input Cost Effects (a)

$$\frac{dQ}{da} = \frac{\alpha E F_{12}}{\Delta} < 0 \quad \frac{dX}{da} = \frac{-\alpha F_{11}}{\Delta} < 0.$$

4. Increases in γ

$$\frac{dQ}{d\gamma} = \frac{Eq(F_2 F_{12} - F_1 F_{22})}{\Delta} < 0 \quad \frac{dX}{d\gamma} = \frac{Eq[F_1 F_{21} - F_{11} F_2]}{\Delta} < 0.$$

5. Discount Rate Effects (δ)

$$\frac{dQ}{d\delta} = \frac{-qEF_{22}}{\Delta} < 0 \quad \frac{dX}{d\delta} = \frac{qEF_{21}}{\Delta} < 0.$$

Factor price effects

A subsidy directed towards the variable input or soil quality improvement capital has a positive own price effect so that the respective input will be used more intensively. This corresponds to the well-known result in the theory of the firm that there can be no Giffen inputs. The cross price effects of reducing one input price on the demand for the remaining input are also in accord with well-recognized theory: the effect is to provide an incentive to expand the use of any other cooperant input.

Effects of increased environmental sensitivity

These effects are captured using the parameter γ. Increases in γ correspond to an increased environmental sensitivity to the intensification of output and have the unambiguous effects of reducing both optimal variable input usage and investment in soil quality. This result is intuitive and indicates merely that intrinsically sensitive marginal agricultural land will be maintained by a rational optimising farmer at relatively low levels of soil productivity. As can be gleaned from Table 1, increases in γ are analogous to the long-run effects of decreased product price.

It is worth emphasising that this is a local result which is based on the assumption that, with increased sensitivity, it remains optimal *not* to mine the soil resource. With non-infinitesimal increments in environmental sensitivity it becomes increasingly likely that equation (9) defining the marginal product of soil capital will not have an interior solution whence it will become optimal to deplete the soil resource without (ever) investing in soil quality.

Discount rate effects

Increases in the discount rate act analogously to increases in capital costs and have the unambiguous effect of reducing investment in soil quality. This effect spills over into a reduced demand for the variable input itself if the latter and land quality are complementary inputs. These results are very straightforward provided, as with the analysis of increased environmental sensitivity, it remains optimal not to mine the soil resource after such a change.

Note however that, while the key condition for the policy system to converge to a steady state with positive sustained investment (namely (12)) is independent of the discount rate, as emphasised above, with a large enough discount rate soils will eventually be abandoned. The key factors involved in determining this are discussed further below.[10]

[10] A number of critics of earlier drafts of this paper found surprising the finding that the effects of prices on soil maintenance apparently depended *only* on whether or not inputs were Edgeworth complements and not on the discount rate. The point is that

cont.

It is worth discussing the case where inputs are Edgeworth substitutes since it is often argued that fertiliser (or pesticide) inputs increase output but do so by reducing soil quality.[11] In this event it is possible (although not inevitable) that increases in product prices can reduce the demand for either soil quality investment or fertiliser (or both). Soil quality is then an *inferior* input. If such price rises do cause a decrease in land quality investment then it must be the case that a fall in the price of such investments leads to lower equilibrium output (this is a well-known consequence of the homogeneity of input demands) and, from Table 1 item 3, it must also be the case that increases in what is termed above 'environmental sensitivity' will increase the equilibrium investment in soil quality. While these types of effects cannot be ruled out on the basis of the restrictions customarily made in analysing producer behaviour, they seem less plausible than the unambiguous implications that stem from the assumption of input complementarity.

Most importantly, if soil quality and an input such as pesticide or irrigation water are substitutes then subsidies directed towards that input will reduce soil quality by encouraging excessive use. Chemical fertilisers can likewise substitute for (rather than complement) organic manuring and other soil conservation practices.

Note finally from Table 1 that, assuming complementarity, the various price, environmental sensitivity and discount rate effects work in the same direction for both inputs used. Since marginal products are positive this means (from (1)) that favourable price effects always bring about *output intensification* which, by considering (4) alone, one would expect to be soil-degrading. This however occurs in conjunction with increased investment in a viable soil quality investment program which, on balance leads to a net increase in soil quality. Increases in environmental sensitivity and discount rates lead to *output deintensification* via reduced usage of each input.

The general comparative static conclusions here are entirely consistent with a somewhat new view of the land degradation issue which sees agricultural land and soils as essentially a *produced rather than primary input* analogous to many other inputs used in agriculture. Thus land degradation and restoration/rehabilitation issues are essentially being viewed as *preventative maintenance* and, perhaps, *repair*

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provided the system does converge to an interior soil quality equilibrium this result is correct. With higher discount rates such convergence becomes less likely. Without convergence the qualitative impacts of price changes (as shown in Section 4) are reversed so the signs of these price multipliers do *in fact* hinge crucially on discount rates.

[11] In fact use of fertiliser is often used as a measure of the burden agriculture places on the environment. This measure of 'burden' has risen dramatically in many countries over the last two decades, particularly in Asia: see Crosson and Rosenberg (1989, p. 132).

problems, i.e., as issues in *replacement investment* analysis, with modifications to soil quality corresponding to capital investments or disinvestments. The extent to which such an input will be produced, and hence the extent of arable lands, depends on the existence of technologies for efficiently utilising and reclaiming land as well as the demand for land. As profitable technologies for usage and reclamation become viable and the demand for land increases, land supplies for agriculture will also increase. At the global level these types of pressures increased world land supplies by 9 per cent from 1950 to 1960 and by 7.4 per cent from 1961 to 1971 (the evidence here is assembled and discussed in Simon (1981, pp. 81-89)). This highly aggregated evidence is treacherous to interpret since of the 123 million hectares of new crop land created over the past twenty years much has originated from forest clearing — about 90 million hectares of forest have been cleared in Latin America alone (see World Resources Institute (1989, p. 263)). There is little hard evidence however that the productivity of agricultural land has fallen overall over recent decades.[12]

4. *Existence of Interior Steady States*

The results of the analysis are clear cut but what is left unexplained is the widespread view that agricultural subsidies will typically lead to worsening land degradation. This view stems from three notions:

1. The effect of subsidies in encouraging farmers who produce a given crop type to utilize increasingly marginal lands (e.g. drylands) which are more susceptible to environmental damage.
2. The role of subsidies in encouraging farmers to switch crop types toward more environmentally damaging varieties.
3. The notion that due to the nonexistence of viable conservation technologies farm land may either not be utilized as a renewable resource (and rather be mined, depleted and eventually abandoned) or, alternatively, that it may be optimal to maintain the land as a renewable resource without investing in soil quality i.e. that soils may be *naturally* self-renewing.

Issue 1 here can be analysed using the framework of Section 3. Since output subsidies increase the value of the productivity of marginal lands it is correct to infer that such subsidies provide incentives for their use. Once such lands are being utilised however the proceeding analysis can be applied: if soil quality is cooperant with other inputs and the marginal lands are being used sustainably, then price increases

[12] The United States has some of the best data relating soil erosion to agricultural productivity. If current erosion rates prevailed for one hundred years crop yields would fall 3-10%. Technological changes, that are modest by historical standards, would much more than compensate for such losses: see Lal (1987), Crossen and Rosenberg (1989).

will reduce degradation. To the extent that such soils are mined, subsidies will have the effects analysed with respect to issue 3. It should be also emphasised that product price rises provide increased incentives for the *creation* (or restoration) of soils that were previously unusable.[13]

The resolution of issue 2 seems *a priori* indeterminate without an additional explanation of why such subsidies should favour relatively degrading activities rather than the reverse.[14]

The single remaining critical issue thus seems to be issue 3. When, in fact, will it be optimal to either manage land resources as exhaustible resources or as a naturally self-renewing renewable resource? This is equivalent to asking when there will *not* exist economically viable soil investment programs given the implication that, without such a program, soils will either be permanently exhausted or sustained only naturally by natural replenishment.

In terms of the model developed so far natural self-renewal is impossible. The only issue is whether or not soils will be depleted. This question can be re-phrased in terms of the conditions whereby equations (9) and (10) do not admit interior solutions. In this event the policy system T does not converge to a steady state where activity continues, because soils are eventually depleted. Sufficient conditions for noninteriority, i.e. the nonexistence of viable conservation technologies, are (as mentioned earlier) that $E < 0$ and that discount rates and environmental sensitivities be sufficiently large.[15] Verbally a variety of situations can be determined where these sufficient conditions are not met:

(i) $\alpha < \gamma q/P$ so that investment in soil quality is sufficiently ineffective in increasing quality.

[13] Davidson (1989, p. 1) writes 'Some of the world's most productive agricultural land, such as the Polders of the Netherlands, were reclaimed from the sea. The fertile wheat lands of east Anglia in the United Kingdom and the plains of Flanders are reclaimed swamps which had no agricultural value before they were drained . . . Similarly deserts have been converted to agricultural land by irrigation'.

[14] If lands are currently employed in some low damage use such as forestry or grassland, then their use for cropping may lead to a deterioration in soil quality. The analysis we have developed shows only that, under mild conditions, existing cropland will be more kindly treated with price subsidies. The model does not show that the rate of damage will be lower under crops than alternative uses. Our point in the text is simply that while changes in product and/or factor prices *may* induce shifts in agricultural production towards environmentally damaging products there is no *a priori* presumption that the shift will operate in one direction rather than the opposite direction. It may in fact lead to increased levels of environmental protection.

[15] To recapitulate (9), (10) can be written compactly as $EF_1 = q(\delta+\beta)/\alpha$ and $EF_2 = a$. For these to possess non-negative solutions in Q, A clearly $E = P - q\gamma/\alpha > 0$ while for non-zero solutions it must not be the case that $q(\delta+\beta)/E > \max F_1$ or $q/E > \max F_2$. In all these conditions increases in P (or falls in a,q) make it more likely that interiority will prevail.

(ii) $q > P\alpha/\gamma$ so that investment in soil quality is prohibitively expensive.
(iii) $\gamma > P\alpha/q$ so that output increases have an excessively strong effect on land degradation.
(iv) δ and β are so large (i.e. discount rates and soil quality depletion rates are so large) that (9) does not have an interior solution.

In these cases it will be non-optimal to (ever) invest in soil quality and the task facing the farmer is simply to select a time path for output which optimises the intertemporal returns from mining soil.

Now a model is formulated that is general enough to analyse such cases and, in addition, can clarify situations where utilisation of natural renewability alone is optimal.

Define the farmer's restricted cost function as:

$$c\,(Y, Q) = \min wx \text{ with } Y = F(x,Q)$$

where x is a vector of variable inputs and w is a conformable input price vector. Make the specific assumptions:

$$C_Y > 0, C_{YY} > 0, \; C_Q > 0, C_{QQ} > 0, C_{YQ} < 0.$$

These restrictions seem very reasonable when inputs are complements — they are trivially satisfied for a Cobb-Douglas technology with a single variable input.

The production planning problem we now address is:

$$\left.\begin{aligned} &\max \int_0^\infty e^{-\delta t}\, PY - C(Q, Y)\, dt \\ &\text{subject to } \dot{Q} = H(q) - \gamma Y. \end{aligned}\right] \quad T'$$

where, in turn,

14(a) $H(Q) = -\beta Q$

14(b) $= k$, a positive constant

$= \text{a } C^2$ strictly concave renewal function with

(14c) $H(0) = H(Q*) = 0$ for $Q* > 0$.

With specification (14a) we return essentially to the model of Section 3 with the modification that investment in soil quality is ruled out. In this event the task T' is a modified Hotelling-type exhaustible resource problem. With (14b) the model corresponds to a modified McConnell (1983) type model with static prices and no technical change. The idea here is that soil renews very slowly at a constant rate k that is independent of the current state of the soil (specifically, whether it is degraded or not). With (14c) the soil-management program is represented as a standard renewable resource problem of the type analysed in the fisheries literature (compare Clark (1976)). This seems more realistic than the McConnell specification since it implies low rates of soil regeneration when soil is already severely degraded.

It also avoids the unrealistic implication that soils left fallow increase in quality without limit.

For renewal function (14a) using standard methods, an equilibrium soil-mining program can be shown to imply that soil quality Q satisfies:

$$P = C_Y$$

One can then deduce that since the level of soil quality can never reach an equilibrium if $\beta > 0$ but will reach an equilibrium when $\beta = 0$ when usage ceases (this is clear from the fact that $\dot{Q} = 0$ if $Y = 0$). In this latter abandonment equilibrium:

$$\frac{dQ}{dP} = \frac{1}{C_{YY}} < 0$$

so that increased price reduces equilibrium soil quality in the sense of leaving *abandoned* soil at a lower quality level. This is a direct way of reaching the conclusions of LaFrance (1989), (1990).

For the McConnell equilibrium, with renewal function (14b) equilibrium output is pegged at $Y = k/\gamma > 0$ and equilibrium soil quality is determined as the solution in Q to:

$$P = C_Y + \gamma C_Q/\delta$$

with $k = \gamma Y$.

so that
$$\frac{dQ}{dP} = \frac{\delta}{\delta C_{YQ} - \gamma C_{QQ}} < 0$$

and, again, soil-quality and output prices are negatively related. This is interesting because such a relationship exists in a situation where soils are *not* abandoned. Therefore the rationale for such a relationship is not the necessity of abandonment with optimal management (as claimed in Clarke (1991)) but, more intuitively, to the non-existence of technologies for augmenting soil quality in this modified McConnell setting.

Finally, if all costs in the McConnell formulation are assumed zero then the integrand in T' can be written independently of price. Hence, equilibrium soil quality is itself independent of price — a point argued at length by Barrett (1991): see his Proposition 1.

The McConnell framework itself is questionable because, as mentioned, it is based on the hypothesis of constant soil renewal *independently* of the current extent of soil degradation. With soil renewal dynamics of form (14c) this restrictive assumption is not made. Moreover, in this more general setting, provided the technology exhibits constant returns (so the restricted cost function is linear in output), Clarke and Shrestha (1986) have shown that the renewable resource stock (here soil quality) is again negatively related to price. In this event it is clearly possible that, with sufficiently high prices, it may cease to be optimal to manage soils as a renewable resource and, instead, be optimal to switch to mining them.

To sum up: if there do not exist economically feasible technologies for boosting the productivity of soils then, with or without soil renewal, soil quality will tend to be negatively related to product price. In the exhaustible case, the quality of soils being abandoned decreases as prices rise because more marginal soils now become economic to utilise. In the renewable soil asset case, price increases lower sustained soil quality because revenues rise relative to the soil stock-dependent production costs. It makes less sense to preserve soils in order to lower overall production costs.

In some situations the main option for the farmer seeking to conserve soils is simply to abstain from some production in some sense, i.e., to *deintensify* production. This option involves reduced grazing pressure or perhaps cropping practices which involve leaving land fallow periodically, or perhaps allocating a portion of land permanently to tree-planting. Under these circumstances it is again shown that, in the absence of alternative conservation technologies, the effect of product price rises is to reduce soil fertility through intensification of output. For specificity, consider the case of tree-planting although the discussion is easily adapted to the various ways in which output can be deintensified. Let:

A = fixed quantity of available land,

x = area of land planted with trees,

A-x = area of land allocated to 'cropping',

$F(x)$ = agricultural productivity of soils per hectare with $F' > 0,\ F'' < 0$,

$C^T(t)$ = cost of maintaining the trees over area t with , $C^T_1 > 0,\ 0,\ C^T_{11} \leq 0$

$C^C(t)$ = cost of harvesting crops over area t with , $C^C_1 > 0,\ 0,\ C^C_{11} \leq 0$

P = output price of agricultural production,

π = steady state profits from agriculture.

For simplicity, suppose farmers act to maximise steady state profits. Also assume that, in any optimum, the marginal costs of cultivation exceed those of tree maintenance so:

$$C^C_1 > C^T_1.$$

Then maximising steady state profits means making the optimal compromise between tree-planting to enhance soil quality and direct cropping. This amounts to maximising:

$$\pi = P\,(A-x)\,F\,(x) - C^T\,(x) - C^c\,(A-x)\,.$$

The relevant first-order condition for a maximum is:

$$\partial\pi/\partial x = 0 \;\;\Rightarrow$$

$$-\,PF'\,(x) + P\,(A-x)\,F'\,(x) - C_1{}^T + C_1{}^C = 0\,.$$

The sufficiency condition for a maximum (which we assume satisfied) is:

$$\partial^2\pi/\partial x^2 < 0 \;\;\Rightarrow.$$

$$-\,2PF'\,(x) + P\,(A-x)\,F''\,(x) - C^T_{11} + C^C_{11} < 0\,.$$

Then, from the first-order condition:

$$\frac{dx}{dP} = \frac{F - (A-x)F'}{P\,(A-x)F''(x) - C^T_{11} + C^C_{11}}$$

$$= \frac{C_1{}^C - C_1{}^T}{P\,(A-x)\,\partial^2\pi/\partial x^2}$$

which is negative on the basis of assumptions made confirming that, as argued, increased output prices mean less 'tree-planting' and hence lower equilibrium soil productivity as measured by F.

Note that, as in the standard renewable resource management model outlined above as (14c), the negative relation between prices and soil productivity here stems from the existence of significant harvest costs. If these were negligible then product price changes would have an imperceptible effect on equilibrium cropping intensities and on equilibrium soil quality. This corresponds essentially with a finding argued at length by Barrett (1991): see his Proposition 3.

5. *Case of Many Variable Inputs*

The analysis above stylises the farmer's planning problem by abstracting from the role of labour, water supplies, fertilisers and pesticides and other variable inputs. What can be said in general about the effects of price incentives on farmer production plans when we admit an arbitrary number $N \geq 2$ of variable inputs? In particular, is it still true that price subsidies will increase the incentive to conserve land given cooperant inputs and viable conservation technologies?

It is very difficult to answer these questions without making very precise assumptions concerning the substitutability/complementarity relationships between inputs in the farmer's production process. What *can* be shown is that, in a steady state where farmers maintain farms as continuing operations, the effects of land conservation investments can be analysed in a way that is *qualitatively indistinguishable* from the standard neoclassical theory of a profit-maximising firm.

The framework is as before except that now the farmer is allowed to select an N-vector of variable inputs x at exogenously fixed factor prices v. The farmer's optimisation task is:

$$\left.\begin{array}{l} \max\limits_{I,A,X} \int_0^\infty e^{-\delta t}(PF[Q,A,x] - qI - aA - vx)\, dt \\ \\ \text{with } \dot{Q} = \alpha I - \beta Q - \gamma F[Q,A,x],\ Q(0) = Q_0 \end{array}\right] \quad T''.$$

where F is supposed strictly concave in all inputs. If λ denotes the relevant costate the current-valued Hamiltonian G is:

$$G = PF[Q,A,x] - qI - aA - vx + \lambda\dot{Q} \tag{15}$$

and necessary conditions for an interior optimum require

$$\partial G/\partial A = 0$$

$$\Rightarrow\ (P - \gamma\lambda)F_2\,[Q,A,x] = a \tag{16}$$

$$\partial G/\partial A = 0$$

$$\Rightarrow\ \lambda = q/a \tag{17}$$

$$\partial G/\partial x_i = 0$$

$$\Rightarrow\ (P - \gamma\lambda)Fx_i\,[Q,A,x] = v_i \text{ all } i \tag{18}$$

$$\dot{\lambda} = (\delta + \beta + vF_1)\,\lambda - PF_1\} \tag{19}$$

In steady state equilibrium where $\dot{\lambda} = 0$ when $\lambda = q/\alpha$ we have from (16)-(19):

$$\left.\begin{array}{l} (P - \frac{\gamma q}{\alpha})F_1[Q,A,x] = (\delta + \beta)q/\alpha \\ \\ (P - \frac{\gamma q}{\alpha})F_2[Q,A,x] = a \\ \\ (P - \frac{\gamma q}{\alpha})F_x[Q,A,x] = v \end{array}\right] \tag{20}$$

where F_x denotes the column vector of partial derivatives of F with respect to x.

Now define Q^*, A^*, x^* as the solutions to:

$$\left.\begin{array}{l} P^*F_1[Q,A,x] = q^* \\ P^*F_2[Q,A,x] = a \\ P^*F_x[Q,A,x] = v \end{array}\right] \tag{21}$$

where $P^* = P - \gamma q/\alpha > 0,\ q^* = (\delta + \beta)q/\alpha$.

These solutions give profit-maximising input levels when factor prices are q^*, a, v and product price is P^* and when all inputs are variable. The complete comparative static properties of these input choices are well-known: see Intriligator (1978, p. 259). The bridge-relations between the comparative static multipliers for system (20) and those for (21) are set out in Table 2.

TABLE 2
Long-Run Degradation and the Standard Neoclassical Model

1. Effects on Land Quality

$$\frac{dQ}{dP}=\frac{dQ^*}{dP^*}, \quad \frac{dQ}{dq}=PF_1\frac{dQ^*}{dq}<0,$$

$$\frac{dQ}{da}=\frac{dQ^*}{da}, \quad \frac{dQ}{dv_i}=\frac{dQ^*}{dv_i}.$$

2. Effects on Land Area Used

$$\frac{dA}{aP}=\frac{dA^*}{dP^*}, \quad \frac{dA}{da}=\frac{dA^*}{da}<0,$$

$$\frac{dA}{dq}=\frac{dA^*}{dq}, \quad \frac{dA}{dv_i}=\frac{dA^*}{dv_i}$$

3. Effects on Use of Other Factors

$$\frac{dx_j}{dP}=\frac{dx*_j}{dP}, \quad \frac{dx_i}{dv_i}=\frac{dx*_i}{dv_i}$$

$$\frac{dx_i}{dq}=\frac{dx*_i}{dq}, \quad \frac{dA}{dv_i}=\frac{dA^*}{dv_i}$$

As in the two input cases analysed earlier there are no Giffen inputs so a subsidy directed towards conservation investment acts unambiguously to increase steady state soil quality. From a practical policy perspective, however, there are substantial qualifications that need to be recognised if this apparently robust result is to be utilised: see Kirby and Blyth (1987, p. 169).[16] The cross-price effects of factor price

[16] In particular Kirby and Blyth argue that subsidies directed towards a conservation input may lower the private opportunity cost of land degradation by reducing the costs of repair. Hence subsidies provide incentives to adopt practices which are relatively more conducive to land degradation thereby offsetting, to some extent, the direct effects of such subsidies.

changes are however ambiguous (in general) as are the effects of product prices changes. All that can be said with respect to the latter is that, using the well-known relationships:

$$\frac{dQ}{dP} = -\frac{dy}{dq}$$

$$\frac{dA}{dP} = -\frac{dy}{da}$$

$$\frac{dx_j}{dP} = -\frac{dy}{dv_j} \text{ all } j$$

it is certain that, if subsidies directed towards inputs increase equilibrium output, then a fall in product prices will certainly increase the use of the same inputs.

This last assumption seems very *plausible* at least with respect to subsidies directed towards land conservation investments. It is not however guaranteed by the qualitative assumptions adopted thus far. If this last assumption is adopted then the price conclusions derived in the previous section for the case of two inputs generalise to the many variable input case.

In concluding this section it is worth noting that, using the methods of Brock and Malliaris (1989, pp. 199-224), the long-run comparative statics of land degradation and conservation can be linked to the issue of convergence to an interior steady state and the latter hypothesis used to generate qualitative results even when a subset of inputs used is *quasi-fixed*. Analogous conclusions to those presented above are known to obtain (e.g. long-run factor demands are downward-sloping) but new additional insights are also possible (e.g. in the two input case it can be argued that complementarity relations must dominate substitutability in production processes).

6. *Final Comments*

The effects of price changes on land degradation have been analysed and it has been shown that the relationship depends crucially on the existence of viable soil conservation technologies as well as the complementarity/substitutability relationships between inputs.

Given such technologies, and complementarity between conservation investment and an input, profitability increases induced by favourable factor or product price movements increase the marginal value product of each input, leading to more intensive use of each and lower equilibrium soil degradation. In this type of setting, if soil losses and other forms of land degradation impose on-site or off-site externalities, then appropriately-directed subsidies will improve soil quality by encouraging conservation. In addition, higher prices stemming from increased demand or reduced supplies, will result in an increased incentive to protect soils. Thus, market mechanisms themselves will operate to reduce the pressures of soil degradation, by encouraging conservation, contrary to the claims of authors such as van Vuuren (1986).

Furthermore, in the absence of externalities, the mechanism here simply involves farmers with access to cost-effective conservation technologies having incentives to use them — an argument that forms the essence of the case for *laissez-faire* in agriculture as argued over (at least) a twenty-year period by agricultural economists such as Bruce Davidson (1969, 1989). From this perspective (and again ignoring land-use externality issues), the key policy issues for governments remain the various public good issues associated with the development of appropriate conservation (and land-restoration) technologies.

On the other hand, the limitations of these types of arguments for *laissez-faire*, even in straightforward deterministic production models, are apparent. If inputs are substitutes then, even given viable technologies, soil quality may decline as the value of the marginal product of investment in soil conservation increases. Without viable conservation technologies, subsidies act to increase the instantaneous rate of land degradation at any level of soil quality and to reduce the equilibrium level of soil quality. This is true regardless of whether eventual soil abandonment is optimal or whether natural renewal can be relied on to sustain soil stocks.

Which of these two scenarios (sustained investment or exhaustible/naturally renewable) is more realistic depends on the values of economic and technical parameters that characterise soil depletion processes. When investment in soil quality is effective, the price of improving soil quality is low, or when increased output has a sufficiently weak effect on land quality, the sustained conservation investment paradigm is appropriate. In the alternative case it is best to view soils either as a depletable resource and apply the relevant theory from Hotelling-like models of exhaustible resources, or else apply the renewable resource models that have been customarily applied to fishery and aquifer problems.

It is reasonable to question the plausibility of the underlying assumption of farm optimisation (with foresight) over an unending time horizon. This seems, at first sight, unrealistic although, as McConnell (1983) has shown, this objective amounts to selecting production plans which maximise discounted returns over *any* finite time horizon as well as the discounted resale value of a farm. The latter consideration will encourage farmers to practice conservation *provided farm values fully reflect soil quality*. The empirical evidence on this issue has in the past been unsupportive of the hypothesis that conservation investment is fully capitalised into farm prices: see e.g. Ervin and Mills (1985), Gardner and Barrows (1985). Recently, however, King and Sinden (1989) have applied the hedonic approach to a sector of the Australian farmland market and were unable to reject the hypothesis that markets acted to conserve soils. This is important for the purposes of this analysis since it confirms the reasonableness of the specification of farmer objectives. Of course the pure logic of the approach used here does not hinge on the validity of such empirical enquiry.

Finally, in Clarke (1992) first steps are taken towards generalising the above analysis into a *spatial* setting where soils of different qualities are utilised. The positive relation between soil quality and product prices identified above is shown to generalise in such a setting when costs are convex in the rate of soil quality investment regardless of whether farmer expenditures are budget-constrained or not. Introducing non-reproducible sources of soil quality leads to differential expenditures on quality (over space) but the positive relation between quality and product price remains.

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