University of Wisconsin-Madison

July 1995 (revised May 1996) No.385

ECONOMIC MODELING OF LAND DEGRADATION IN DEVELOPING COUNTRIES

By

Ian Coxhead

AGRICULTURAL
AND
APPLIED ECONOMICS

STAFF PAPER SERIES

Economic Modeling of Land Degradation in Developing Countries

Ian Coxhead[1]

Abstract

The history of economic models of land degradation is short, and yet fundamental changes have occurred in the structural assumptions underlying land degradation models and the questions they are used to address. Many of these changes are the results of studies in developing countries, where the problem of land degradation is proportionally much more severe. In this paper I first review the conventional single-farm approach, then present and explore some recent modifications and extensions. In an era of sometimes sweeping economic change in developing countries, the relationship between agricultural prices and land degradation is of particular importance. I examine ways in which different models predict the likely land degradation effects of economic reforms.

University of Wisconsin-Madison, Department of Agricultural and Applied Economics
Staff Working Papers No.385, July 1995 (revised May 1996).

I Introduction

Scope and Severity of the Problem

The relative decline of agriculture is a long-established fact in virtually all economies. Paradoxically, however, the problem of soil erosion and of associated forms of agricultural land degradation commands increasing attention both in legislatures and in research institutions.[2] Newly discovered and more cogently articulated concerns with pollution and the depletion of natural resource reserves have helped focus attention on the question of whether current patterns and growth rates of agricultural production are sustainable, in the sense that future generations will face the same production and consumption opportunity sets as are faced today.

The concern is not only with future generations. The supply of clean water, available at a predictable time and place, is strongly influenced by agricultural conditions. Demand for water with these attributes grows at least as fast as population, and much faster with economic transformation and rising real per capita real income. Thus even if little is known about the on-site effects of land degradation, its offsite effects in the form of diminished water quality and quantity are subject to increasingly close scrutiny.

Accurate estimates of the economic costs of agricultural land degradation are very difficult to obtain. In the U.S., Ribaudo *et al.* (1989) estimated the 1981 value of off-site water-borne damage from agricultural soil erosion at $3.5 billion; more recently Pimentel *et al.* (1995) calculated the annual value of soil erosion in U.S. agriculture at $US 44 billion, of which $17 billion was attributed to off-site damage. Other accounting studies in developing countries indicate proportionally much larger losses: 1-4 per cent of GDP in in Indonesia and the Philippines (World Bank 1989,1990); 8% in Costa Rica (TSC/WRI 1991); 9% in Burkina Faso, and as high as 17% in Nigeria (Barbier and Bishop 1995). In wealthy and poor countries alike, governments are absorbing the magnitudes of estimates like these and beginning to grapple with the question of an appropriate policy response.

While accounting exercises indicate the scope of the problem, economic models help explain the causes and consequences of land degradation in terms of institutional and market phenomena, and thus provide links from problem to policy instruments. In this paper I focus on modeling and policy issues organized around specific questions relating to the causes and consequences of land degradation (for more complete treatments and bibliographies see Blaikie 1985; Blaikie and Brookfield 1987, Chisholm 1992, and Anderson and Thampapillai 1990). Two main questions are posed. First, how can changes in the prices of agricultural goods be expected to alter farmers' decisions affecting land degradation? Second, in assessing erosion damage, what role is played by economic and physical links between agriculture and other sectors? Addressing these two questions contributes to an answer to one now frequently confronted in developing economies: what are the likely land degradation impacts of economy-wide economic reform?

Economic analysis of land degradation has a long history (Bunce 1942; Ciriacy-Wantrup 1968); however, formal modeling of the subject is relatively new. Initial modeling efforts concentrated on farm-level analyses, which by adddressing farmer' resource allocation and investment decisions in detail are well suited to address the direct causes of land degradation. I review several such models in the next section. Subsequently I examine some research and policy questions to which they have been applied; in particular, whether a price increase promotes land degradation or stimulates soil-conserving investment. However, some of the partial equilibrium assumptions underlying farm-level models may be questionable, particularly in developing economies; accordingly, in a fourth section I present a simple general equilibrium framework of the causes and impacts of land degradation. In a final section I draw some conclusions and present an agenda for future research.

II Farm-level resource allocation and land degradation

The formal analysis of land degradation begins with optimal control models by Burt (1981) and McConnell (1983), and an erosion damage function analysis by Walker (1982). The Burt, McConnell and Walker (hereafter BMW) models posit price-taking producers who aim to maximize the net present value of output. These producers' decisions are conditioned in part by a measure of soil quality that captures the effects of past agricultural practices; the farmer’s problem is essentially to find the optimal rate of soil (or soil quality) depletion.

In Burt's seminal paper topsoil depth (x) and soil organic material (y) are state variables whose current values are determined by past crop choices -- specifically, the fraction of land planted to wheat, a relatively erosive crop. With this fraction denoted by u, the evolution of soil depth and organic matter content are described by state equations incorporating the loss functions ϕ and h:

$$x_{t+1} = x_t - \phi(x_t, y_t, u_t) \qquad \phi_u > 0,$$

and

$$y_{t+1} = y_t - h(x_t, y_t, u_t) \qquad h_u > 0.$$

Farm yields are progressively reduced by topsoil loss and diminution of soil organic material, so for given prices, and without compensating increases in fertilizer input, the profitability of planting wheat is a declining function of u. The farmer's problem is then to choose u_t in each period to maximize the present value of net farm income:

$$\sum_{t=1}^{\infty} G(x_t, y_t, u_t)/(1 + r)^t \qquad G_u > 0.$$

Maximization of G subject to the soil depth and organic matter variables, and (together with appropriate stability conditions and terminal values) provides optimal values of the control variable u. Although Burt used U.S. data to provide a numerical solution to this dynamic optimization problem, the underlying model is reasonably general, which helps explain its longevity in soil erosion studies. One obvious limitation, however, is that the only means to influence the values of state variables is by reallocating land between wheat and the less erosive crop. It follows that an increase in wheat prices, by increasing G, ϕ and h, unambiguously increases soil erosion.

Walker addresses choice of technique, introducing as a control variable the time of adoption of a soil-conserving practice. Farmers decide each year whether or not to adopt the practice, based on a damage function recursively comparing the net present value of another year's use of an erosive practice with that of immediate adoption of the soil conserving one.[3] Other things equal, for some rate of erosion-related yield decline it may become profitable to adopt soil conservation even if the current costs of doing so are higher than for the erosive practice - as for example when some land must be set aside to plant grass strips or hedgerows.

McConnell introduces a policy dimension by comparing private and social returns to farmers' land use decisions. In his analysis farmers choose inputs to maximize the present value of a stream of output given by:

$$J = \int_0^T e^{-rt}[ph(t)G(s, x, z) - cz]dt,$$

where r is the discount rate, p is the price of output, $h(t)$ is a neutral technical change shifter, and the benefit function G is is determined by soil loss $s(t)$, soil depth $x(t)$, and an index of variable inputs $z(t)$ with unit costs c. The problem is thus set up in a way similar to Burt, except that here soil loss is included among current inputs, making it a control rather than a state variable.[4]

Soil loss helps in turn to determine the time path of soil depth (x):

$$\dot{x} = k - s(t),$$

where k is the autonomous natural rate of soil regeneration, and thus defines the tolerance value ("t-value") of the rate of soil loss. While a steady state ($\dot{x} = 0$) is in principle achievable, for a positive discount rate the socially optimal rate of soil loss may exceed k. The likelihood of this will be greater if purchased inputs z (for example fertilizer) are substitutable for soil depth, or if technical progress enables net revenues to rise even as the soil stock is depleted. McConnell's major contribution is to observe conditions under which it may be privately optimal for farmers to make production choices in which $s(t)$ exceeds both the natural regeneration rate k and the socially optimal rate. If real asset markets are not efficient, for instance, then farmers on rented land may truncate their planning horizons, thus introducing a soil-depleting bias. Alternatively, if capital markets are not efficient then farmers' rates of time discount may exceed the market rate of return on capital. Perhaps the strongest conclusion from McConnell's analysis is that "if financial and real asset markets work efficiently, private farmers may follow the socially optimal path" (p.88) of soil depletion, by being induced to discount the welfare of future generations at a rate equal to that which maximizes social welfare.

Considered together, the BMW models capture the key features of the farm-level optimal depletion problem: farmers choose crops and techniques to achieve an optimal soil or soil quality depletion rate for given prices, discount rates and planning horizons. Each study provides a vehicle for examining the influence of one or more exogenous factors -- prices, interest rates, and/or natural rates of regeneration -- on the privately optimal rate of land degradation. Each highlights the critical empirical question of the rate at which an erosive practice contributes to land degradation, although only McConnell distinguishes formally between this and the socially optimal rate. Given the quality of these contributions it is hardly surprising that the methodology of most contemporary land degradation models derives from this body of work.[5]

Soil-conserving investments

In the BMW models the actions of farmers can only reduce the stock of soil, albeit at differing rates. In recent years, however, as the emphasis in natural resource modeling and management has shifted from optimal depletion to one of 'sustainable use', the characterization of land degradation as a problem of the optimal depletion of an abundant resource has been reevaluated. A number of models have been developed that allow for soil quality-improving investments (Barbier 1990; Clarke 1992; LaFrance 1992).[6] Clarke (1992) has characterized the assumption that soil quality can be increased by investment as well as being depleted as:[7]

> ... 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 ... issues in *replacement investment* analysis, with modifications to soil quality corresponding to capital investments or disinvestments (pp.44-45; emphasis in original).

The possibility of soil-enhancing investments extends the range of the farmers' options with respect to production and resource allocation; in addition to choosing technologies and crops, the optimization problem now includes the allocation of resources between current production and future soil quality. Incorporating this and some other generalizations, the farmer's problem may be restated as:

$$J \;=\; \max(\mathbf{z}) \int_{t=0}^{\infty} e^{-rt} \left\{\mathbf{p}[\boldsymbol{f}(\mathbf{x}, \mathbf{z}, \tau)) - c(\mathbf{w})\right\} dt,$$

where **p** is a vector of prices corresponding to outputs produced by processes ***f***; **x** is a vector of determinants of soil quality; τ is a measure of technological progress, and $\mathbf{z} = \{z_1, z_2\}$ is a vector in which z_1 is an input to current production, while z_2 is an input to preserved or enhanced soil quality. The cost function $c(\mathbf{w})$ has as its arguments the prices of z_1 and z_2. J is maximized subject to the equations of motion of the state variable(s), the srguments of which are u, the share of land devoted to the relatively erosive crop (assuming only two crops as in Burt); k, the natural rate of regeneration as before, and z as just defined:

$$\dot{x} \;=\; \mathbf{g}(k, \mathbf{z}, u) \qquad \partial g/\partial k > 0,\; \partial g/\partial z_1 < 0,\; \partial g/\partial z_2 > 0,\; \partial g/\partial u < 0,$$

Models of the BMW type are now seen to be special cases in which $\partial g/\partial z_2 = 0$: farmers' actions can only deplete the soil, albeit at varying rates depending on crop and technology choices.

The intertemporal link provided by the investment variable alters the comparative static and steady state properties of the BMW models (see Clarke for an analysis). Moreover, the empirical significance of this 'new' view of land degradation becomes apparent when we consider farmers' responses to exogenous economic changes.

III Policy and empirical issues in farm-level analyses

Do higher prices cause more rapid land degradation?

A growing literature asks whether increases in agricultural profitability tend to promote soil mining or soil conservation. Debate on the question covers both policy and methodology. We address methodology in this section and return to policy questions later, in the context of a discussion of the effects of economic reform in developing countries.

A uniform increase in agricultural prices could affect resource allocation within the current period as well as altering incentives to undertake soil-conserving investments. Moreover, if relative prices change, then corresponding changes in the optimal input and output mixes could also influence land degradation rates. Individual aspects of this analysis are captured in each of the BMW models (e.g. Burt's analysis of the effects of changing output mix) although none is sufficiently general to capture the full range of possible responses to price changes.

Under what circumstances might farmers be inclined to adopt soil-conserving technologies in response to higher output prices? As we have seen, the structure of most early models makes it inevitable that farmers will plant more of an erosive crop. The exception is Walker's model, which illustrates the choices farmers face when only one crop is grown. Suppose an erosive rather than a soil-conserving technology is used initially, in year 1. In the future, either yields will be lower or production costs higher, for example if farmers compensate for lost soil quality by applying more fertilizer. The present value of the net benefit stream from year 2 onwards could therefore be either higher or lower than if the soil-conserving technology had been adopted in Year 1. Suppose Year 1 yields are higher under the erosive technology. The probability that an unanticipated permanent rise in output price will retard adoption of the soil-conserving technology is then greater if producers are myopic and/or if yield losses with the erosive technology are slight compared to the soil-conserving technology. Conversely, if the rate of time discount is low, or if the yield loss difference is high, a price rise will tend to encourage earlier adoption of the soil-conserving technology.[8]

Newer models provide more general answers to the price change question. In particular, Clarke (1992) demonstrates that if soil quality is complementary with other inputs to production, then higher product prices, by raising the value marginal product of the complementary inputs, will thereby increase the return to an investment in improved soil quality (analogous results hold for the case of input subsidies). This and similar papers demonstrate that either land-degrading or land-preserving responses to output price increases might be observed, depending on the yield impact of erosive practices and the soil-conserving impact of investments.

The apparent lack of ambiguity of earlier models on this point thus resolved, normative debate over the potential for price rises to increase land degradation now hinges on empirical questions: the validity of 'standard' market assumptions, and the values of parameters governing agricultural supply response, technology, and land degradation rates. In the remainder of this section I address some of the former. I focus mainly on developing countries, where information on these points is most scarce, and debate most sharply defined, due to the relative scarcity of soil resources and the higher degree of dependence on agricultural income.

Nonconvexities and the vanishing 'A' horizon

The depletion of a finite resource may result in non-marginal changes, such as a cessation of production as stocks are exhausted. Such nonconvexities have yet to be incorporated in soil erosion models, perhaps because most such models have been developed for the study of erosion in areas characterized by very deep topsoils. In the uplands of developing countries, however, topsoil resources are typically very scarce: the rooting zone may be no more than a few centimeters deep. Erosive practices may quickly exhaust this resource, thus altering *in situ* soil structure -- an additional feature of erosion not accounted for in the BMW models. Topsoil removal will also cause increasingly rapid rates of soil fertility decline (lower soil strata are less fertile), and may produce permanent changes in soil structure or even a truncation of the yield function at some level of cumulative soil loss. Thus land abandonment is a phenomenon frequently observed among farmers in the uplands of developing countries.

Other things equal, shallow topsoils and less fertile substrata increase the present value of early adoption of soil-conserving crops and technologies, since these defer the date of land abandonment. A recent study of upland vegetable cultivation in the Philippines adapts Walker's model to developing country conditions, modeling the productive soil resource as finite by placing an upper bound on years of cultivation given cumulative erosion (Hoang 1994). The analysis of a soil-conserving investment (bench terrace construction) is very sensitive to the imposition of this threshold; the benefit-cost ratio of terrace construction is several times higher than that indicated when the yield function of the erosive technology is not truncated .

Missing markets and endogenous prices

In industrialized countries the neoclassical single-farm model is an appropriate vehicle for analysis of the on-site impacts of agricultural land degradation. The atomistic, price-taking commercial farm is a convenient and obvious unit of analysis; institutional conditions are relatively uniform across farms within broad regions, and agriculture as a sector is too small to affect prices elsewhere in the economy. In developing countries, by contrast, region-specific physical, economic or institutional conditions are widely regarded as of sufficient importance to require major departures from neoclassical conventions. Fixed costs, informational constraints and high transport and marketing margins are all constraints to technology adoption and crop substitution, and in addition constitute potential sources of imperfect competition (Benson and Faminow 1990). Risk aversion and non-separability of the production and consumption decisions made by poor households may also be important in some regions (Singh, Squire and Strauss 1986). Moreover (as we show in the next section) changes occurring within agriculture may affect commodity and factor prices in many sectors of a developing economy, and the off-site implications of soil erosion thus assume greater importance.

The implications of relaxing the assumption of perfect competition are illustrated in an important study of developing country land degradation by Perrings (1989). Using optimal control techniques, Perrings describes a livestock economy which lacks markets for either capital or insurance; as a result, risk-averse subsistence producers are reluctant to adopt new technologies or products that cannot as easily be consumed directly, and savings take the form of real assets (livestock); in this setting household production, savings and consumption decisions are jointly determined (there is also no labor market). Faced with a minimum subsistence constraint, producers respond to declining resource productivity by increasing the scale of production, so that drought or other natural phenomena (including overstocking) tending to reduce land productivity may provoke farmers to increase - not reduce - herd size. In similar fashion, a terms of trade decline for these producers, if they are wedded to livestock production as both income source and savings/insurance instrument, may cause them to increase herd size and thus, by accelerating the rate of pasture depletion, place themselves on an “optimal path to extinction”. In the language of Sen (1981), a failure of farmers’ trade entitlements with finite soil resources may stimulate a failure of their direct (production) entitlements, as the need to insure consumption levels drives a spiral of increased herd size and reduced soil productivity to the point where the exhaustion of the soil is assured.

Perrings' conclusion that lower agricultural prices might cause land degradation is diametrically opposed to that of McConnell, in which it is higher prices that have this effect. The contrast highlights the importance of structural assumptions in models of this nature. For different reasons, neither model allows for crop substitution or soil-conserving investments; in both, more intensive cultivation leads to more rapid land degradation. However, McConnell is not concerned with the household consumption implications of a terms of trade decline, presumably because labor is mobile. Perrings' households have no opportunity for intertemporal arbitrage or off-farm employment, so if price declines threaten to drive household consumption possibilities below a critical minimum point, they respond by increasing herd size - in effect reallocating their savings portfolio from an illiquid asset (land) to one more liquid (livestock). The lesson is that market failures and subjective poverty condition the range of possible responses to a price change.

Property rights in land

While capital and insurance market failures are central to the Perrings model, other market failures are held responsible for outcomes in which rising prices induce resource degradation in developing countries. Most notable is the problem of ill-defined or poorly enforced property rights (Bromley 1991). In open developing economies, Brander and Taylor (1994), Southgate (1988) among others others have constructed open-access 'tragedy of the commons' scenarios in which the effective absence of property rights in land ensures the private profitability of resource-degrading or depleting activity. In Brander and Taylor, for example, shifting from autarky to trade is seen to be a source of immizerizing growth for a small country having comparative advantage in a resource-intensive commodity when its resource base is open-access and thus susceptible to overexploitation. The authors have forest industries in mind, but their analysis applies equally to uncontrolled expansion of land-degrading agricultural sectors (Thailand's cassava boom in the 1970s is one example).

Risk and uncertainty

In wealthy countries, insurance and government interventions tend to confer stability on agricultural incomes in spite of price and yield fluctuations. In developing countries, by contrast, the lack of such safety nets makes price and yield instability an important concern for many farmers, whether they are net food producers or consumers. Yet the models reviewed so far uniformly impose price certainty and risk neutrality.

Risk aversion is the norm for farm families on the margin of poverty, and price uncertainty may induce overproduction relative to a socially optimal level when land degradation effects are taken into account, as a hedge against both crop failure and price collapse. Even for risk-neutral producers, price instability is a disincentive to investment, particularly in soil-conserving structures or perennial crops with long lead times, since it confers option value on the decision to wait rather than invest (Shively 1996). In developing countries there is a case for closer study of the land degradation implications of changes in the variance of prices as well as their means. The neglect of risk and uncertainty is a major weakness of economic models of land degradation to date.

Does technical progress in erosive crops contribute to land degradation?

Technical progress has made a significant contribution to expansion of food production, especially in developing Asia. However, it plays a minor role in most land degradation models. In those partial equilibrium models that address the subject at all, the effect of technical progress on resource allocation is identical to that of a price rise; other things equal, it causes demands for all inputs (including soil quality) to increase (e.g. Walker and Young 1986). Analysis of the effect of technical change on land degradation thus proceeds as for a relative price change.

This approach to the effects of technical progress is acceptable at the level of the individual farm, for which prices are parametric. Typically, however, productivity gains from technical progress are widespread, and the associated aggregate supply shift may reduce producer prices when these respond to domestic market conditions. Accordingly, even without investments in soil quality, technical progress in an erosive crop could actually lead to reduced land degradation if the productivity gain causes land use for that crop to decline. This seems a likely outcome of technical progress in staple food crops like rice and corn, which are major sources of upland erosion in Asia (Lal 1990), in which trade is usually restricted, and for which demand is typically inelastic (Coxhead and Shively 1995).

There has been surprisingly little discussion of the land degradation consequences of the green revolution.[9] The green revolution had far-reaching effects on the welfare and resource allocation decisions of farm households even in areas where new cereals technologies did not substantially increase yields and were seldom adopted. These effects were felt through endogenous changes in commodity and input prices. Intersectoral and interregional markets for labor and food in developing countries ensured that adoption of green revolution technologies in irrigated lowlands reduced the relative profitability of producing highly erosive food crops such as corn in less productive upland areas. Whether this resulted in more or less land degradation depends on how upland farmers (who are mainly very poor) reacted to the relative price change. If their only link to the rest of the economy was through product markets, their response may have been to increase cropped area to insure consumption targets, in the way predicted by Perrings. Alternatively, given competing land uses, or increases in off-farm income due to labor demand growth in lowland agriculture, upland land may have been reallocated to perennial or less erosive crops (Coxhead and Jayasuriya 1994). More empirical research is required to quantify the net land degradation impact of technical progress in developing country agriculture; it is clear, however, that the question cannot be addressed adequately using single-farm models.

IV The economic context of land degradation

The boundaries of the farm do not contain all relevant information for assessing the consequences of land degradation. Off-site effects of soil erosion (flooding of lowland agricultural lands, siltation of irrigation systems, diminished storage capacity and damage to physical plant in hydroelectric power generation schemes, and water quality deterioration affecting drinking water supplies and the productivity of inland and coastal fisheries) are widely recognized to be at least as important as on-site damages in may areas. Conversely, macroeconomic management, trade policy and other events outside agriculture can exert significant impacts on agricultural production and resource allocation, and thus on land degradation (Cruz and Repetto 1992; Coxhead and Jayasuriya 1995; Pearson and Munasinghe 1995). Analyses that ignore intersectoral causes and consequences of soil erosion therefore risk advancing misleading or even damaging policy advice on agricultural resource allocation.

In this section I present a general equilibrium model of land degradation which captures, in stylized form, the main economic and physical links between sectors producing soil erosion and the rest of the economy. The model provides a vehicle for understanding both the broad economic implications of land degradation, and the land degradation implications of economic changes originating outside agriculture.

The degree of complexity inherent in the multisector, general equilibrium approach of the model makes it desirable to abstract from the intertemporal issues raised in sections II and III. For simplicity we also ignore departures from standard neoclassical assumptions, assuming risk-neutrality, constant returns to scale and competitive markets for goods.

In spite of these restrictions the model demonstrates conditions in which a general equilibrium approach to modeling agricultural land degradation is important. When (as in most developing countries) agriculture is large in relation to domestic markets or trade, assessments of the economic consequences of land degradation must take account not only of the on-site losses addressed in single-sector models, but also of productivity, resource allocation and income effects beyond agriculture. The likelihood that land degradation will worsen aggregate welfare is higher if the degradation generates significant off-site effects.

Our aim is to capture endogenous changes in agricultural land degradation and to measure their aggregate welfare impact. The problem is compactly addressed using duality. For a single economy denote aggregate consumption by an expenditure function $E(\boldsymbol{P},U) = \min\{\boldsymbol{P}\cdot\boldsymbol{Q} \mid U\}$, and aggregate revenue by the GNP function $G(\boldsymbol{P},\boldsymbol{V}) = \max\{\boldsymbol{P}\cdot\boldsymbol{Y} \mid \boldsymbol{V}\}$, where $\boldsymbol{P}$, $\boldsymbol{Q}$ and $\boldsymbol{Y}$ are vectors of commodity prices, consumption and production respectively; U stands for aggregate utility measured as consumption of goods, and $\boldsymbol{V}$ is the vector of the economy's effective (i.e. quality-adjusted) endowments of land (Z), non-agricultural capital (K), and other factors.

Suppose only three goods are produced and consumed: an erosive crop (D), a less erosive crop (C), and a non-agricultural good (N) We use the price of the non-agricultural good as a numeraire, so $\boldsymbol{P}$ is the relative price of agricultural goods. This price in turn is an index of prices of less erosive and more erosive crops, i.e., $\boldsymbol{P} = P_c^{\beta} P_d^{1-\beta}$, where β is the share of the less erosive crop in the total value of agricultural production.

Beginning with the equilibrium condition that aggregate expenditure equals income:

$$E(\boldsymbol{P},U) = G(\boldsymbol{P},\boldsymbol{V}), \tag{1}$$

we seek expressions showing the effects of exogenous changes on aggregate welfare, initally when all goods are traded at given world prices. Totally differentiating (1) and collecting terms in prices gives an expression for the change in real income, dY:

$$dY = -H_p d\boldsymbol{P} + G_v d\boldsymbol{V}, \tag{2}$$

where subscripts on G and E denote partial derivatives of the revenue and expenditure functions with respect to subscripted variables, and dY, the change in real aggregate income, is defined as $dY = E_u dU$ (Dixit and Norman 1980). The term $H_p = (E_p - G_p)$ is the vector of excess demands for goods (imports if positive, exports if negative), and G_v is the shadow price of the v'th factor, which in a competitive economy with no externalities would be equal to its market price.

We now examine the effects of changes in $\boldsymbol{P}$ and $\boldsymbol{V}$ under a range of assumptions about the sources and intersectoral impacts of such changes. We begin by holding $\boldsymbol{P}$ constant and examining changes in the effective endowments of two components of $\boldsymbol{V}$: Z, the agricultural land base, and K, sector-specific capital in the non-agricultural sector.

On-site land degradation

Let Z be the effective amount of land available for agricultural production, defined as the product of $\bar{Z}$, the physical land endowment, and A, an index of land quality. We assume that growth in the physical land area is exogenous. Land productivity is increased by improved management practices (M), including soil-conserving investments, and by technical progress in either the erosive crop (T_d) or the soil-conserving crop (T_c). It is diminished by an increase in the fraction of land devoted to cultivation of the relatively erosive crop, denoted by R. R is in turn a function of two ratios, T_d/T_c and P_d/P_c, denoted Q and S respectively. Given these simple assumptions, write the definition of the effective land endowment as:

$$Z \equiv \bar{Z} \cdot A(M, T_d, T_c, R(Q, S)). \tag{3}$$

We assume $Z_A > 0$ and it follows from variable definitions that $A_M > 0$, $A_R < 0$, $R_Q > 0$, and $R_S > 0$.

Technical progress in either crop raises overall land productivity and in addition alters R, the ratio of erosive to soil-conserving crop area:

$$dZ = \bar{Z} \cdot (A_{Td} + A_R R_S) dT_d \gtrless 0\,; \tag{4a}$$

$$dZ = \bar{Z} \cdot (A_{Tc} - A_R R_S) dT_c > 0. \tag{4b}$$

The net effect of technical progress in the soil-conserving crop is to increase effective land area; however the same is true for technical progress in the erosive crop only if $A_{Td} > A_R R_S$, that is, if the overall productivity gain outweighs the increase in land degradation caused by the shift of land into production of the erosive crop. Finally, by adding (4a) and (4b) and substituting them for dV in (2) we obtain the welfare effect of uniform technical progress in both crops. At constant prices, the sign of the welfare gain from neutral technical progress is the same as that of effective land area growth. In general equilibrium, technical progress in one agricultural subsector or region can induce altered resource allocation in others, so accurate predictions of the aggregate welfare and land degradation effects of technical progress require a multisectoral framework (Coxhead and Jayasuriya 1994).

Exogenous price changes, like technical progress, induce land reallocation between crops. For given physical land area, a rise in P_d reduces the effective area and a rise in P_c increases it, as can be seen by taking the total differential of (3) with respect to each price:

$$dZ = \bar{Z} A_R R_Q P_c^{-1} dP_d < 0 ; \tag{5a}$$

$$dZ = -\bar{Z} A_R R_Q P_d P_c^{-2} dP_c > 0. \tag{5b}$$

While these physical changes are unambiguous, the economic consequences of price changes are not, as can be seen by substituting from (5a) and (5b) into (2) and collecting terms:

$$dY = -(H_d - G_z \bar{Z} A_R R_Q P_c^{-1}) dP_d - (H_c + G_z \bar{Z} A_R R_Q P_d P_c^{-2}) dP_c . \tag{6}$$

Consider an increase in the price of the erosive crop, with $dP_c = 0$. If *D* is a net import, $H_d > 0$. A rise in P_d is then associated with a reduction in welfare, first because it represents a negative terms-of-trade change, and second because it induces a reallocation of land into production of the erosive crop. On the other hand, if *D* is a net export ($H_d < 0$), then the erosion loss is offset by additional income due to improved terms of trade, and the net welfare effect is indeterminate. A similar analysis applies to *ceteris paribus* changes in the price of the soil-conserving crop. We conclude from (6) that some amount of erosion may be socially optimal if the value of additional erosion is more than offset by net gains in foreign currency earnings.[10]

We can simplify interpretation of the foregoing expressions by means of a simple transformation, converting from levels to percentage changes of variables. Let the percentage change in every variable *X* be denoted by a lower-case letter $x = 100*dX/X$. Taking the total differential of (3) with respect to prices and the physical land area and converting to percentage changes, we obtain an expression for the growth rate of effective land area:[11]

$$z = \bar{z} + \zeta\rho(p_d - p_c). \tag{7}$$

At constant prices, growth of effective land area is directly related to growth of physical area. When relative prices P_d/P_c change, the ratio of erosive to soil-conserving crop area (*R*) changes, and this alters the on-site land degradation rate. The net effect of the price change is governed by the values of two parameters: $\zeta = A_R(R/A)$, the elasticity of land quality with respect to a reallocation of land to the erosive crop, and $\rho = R_Q(Q/R)$, the elasticity of agricultural land allocation with respect to P_d/P_c. Since $\zeta < 0$ and $\rho > 0$, a rise in P_d/P_c reduces z by increasing on-site land degradation.

We can now assess the welfare impact of exogenous price changes in the presence of on-site land degradation. Converting (2) to percentage change form, substituting from (7) for the change in V, and collecting terms we obtain:

$$y = -(\gamma_d\mu_d - \delta_z\zeta\rho)p_d - (\gamma_c\mu_c + \delta_z\zeta\rho)p_c, \tag{8}$$

where $\gamma_j = P_jG_j/Y$ is the share of sector j revenues in total real income; $\mu_j = H_j/P_jG_j$ is the value of domestic excess demand for good j as a share of domestic production of j, and $\delta_j = G_zZ/Y$ is the payment to land as a share of total real income. It is now easy to see that an increase in the price of the erosive crop will reduce welfare is that crop is importable; welfare will also tend to decline if D is exportable but has only a small terms of trade effect relative to its land degradation impact. Larger welfare losses will occur if D is a much more erosive crop than C, if payments to land are a large fraction of total income, and if agricultural resouce allocation responds elastically to relative price changes. Conversely, a positive welfare chnage could ensue if the crops differ little in terms of erosivity, or if D is exportable and the terms of trade gain outweighs the value of production from effective land area lost to increased erosion.

So far, the analysis shows that even with exogenous commodity prices and no off-site effects, the single-sector observation that a higher erosive crop price leads to more erosion does not automatically imply that society as a whole will thereby be made worse off. Aggregate welfare effects depend on the size of affected sector, the relative importance of land as a factor of production, between-crop differences in land degradation rates, and the terms of trade effect of the price change. These results hold in a multi-sectoral context even without investment, the mechanism around which the single-sector analyses in section III were seen to turn.

Erosion externalities

We now introduce the possibility that soil erosion generates external diseconomies. For simplicity, suppose that erosion damage affects only the productivity of *K*, the specific factor used in the non-agricultural sector. Define the effective endowment of this input as:

$$(9) \qquad K \equiv \bar{K}\, R(Q,S)^{\alpha},$$

where $\alpha < 0$ captures the off-site effect of agricultural soil erosion, analogous to the on-site effect captured by ζ. A larger absolute value of α indicates that erosion inflicts greater damage on the effective stock of *K*. Totally differentiating (9) and again converting to percentage changes:

$$(10) \qquad k = \bar{k} + \alpha\rho(p_d - p_c).$$

The relative price change alters *K* through changes in the allocation of land between erosive and soil-conserving crops; the rate of reallocation is governed by ρ. The extent to which this change alters downstream factor productivity depends on the value of α. Empirically, the precise nature of a change in *K* depends on the type of activity in the affected sector - whether hydro power generation, irrigation water distribution, coastal and inland fisheries, or another industry affected by increased sediment loading in river water caused by upland soil erosion.

To find the welfare change associated with a price change in the presence of externalities we first express (2) in percentage change form:

$$y = - \sum_{j=c;d} \gamma_j \mu_j p_j + \delta_v v,$$

then use $\delta_v v = \delta_z z + \delta_k k$ (with other factor endowments constant) to substitute from (7) and (10):

$$(11) \qquad y = - \sum_{j=c;d} \gamma_j \mu_j p_j + \rho(\delta_z \zeta + \delta_k \alpha)(p_d - p_c) + \delta_z \bar{z} + \delta_k \bar{k}.$$

$$(11) \qquad y = - [\gamma_d \mu_d - \rho(\delta_z \zeta + \delta_k \alpha)]\, p_d + [\gamma_c \mu_c - \rho(\delta_z \zeta + \delta_k \alpha)]\, p_c + \delta_z \bar{z} + \delta_k \bar{k}.$$

This expression differs from (8) in that it contains additional welfare loss terms associated with the production of off-site damage. Any increase in P_d / P_c has negative environmental impacts both within agriculture, and in non-agriculture through a decline in the effective endowment of *K*. If the erosive crop is importable, the total real income effect of a rise in P_d / P_c will also be negative. Again, however, if the erosive crop is a net export, the net welfare impact of a price change will depend on whether the net foreign exchange gain outweighs, or is outweighed by, the value of additional land degradation and off-site damages in the domestic economy.

Non-traded goods, price policy, and land degradation

We now relax the assumption of exogenous commodity prices, to evaluate land degradation and aggregate income effects of exogenous changes when some price changes themselves depend on changes in effective factor endowments. This structure is particularly well suited to analysis of price or trade policy changes -- interventions of considerable importance to relative commodity prices in developing country agriculture.

Suppose that the erosive crop is not traded, so its price is determined exclusively in domestic markets.[12] Equilibrium in the model now requires an additional market-clearing condition determining this price. Using duality we write this condition as:

$$E_d(\boldsymbol{P},U) = G_d(\boldsymbol{P},\boldsymbol{V}). \tag{12}$$

Simultaneous solution of (1) and (12), using the definitions of on-site and off-site damages in (3) and (8), gives changes in aggregate welfare and $\boldsymbol{P}$ allowing for agricultural land degradation. As before, the interpretation of results is facilitated by working in percentage changes. Totally differentiating (12) and converting to percentage change form, we arrive at a measure of welfare change in which each price change has three effects. The first is a free-disposal terms of trade effect; the other two capture the effects of induced changes in on-site and off-site damages:

$$\begin{aligned} Dy \;=\; &-(\gamma_d\varepsilon_{dd} - \omega_{dz}\zeta\rho - \omega_{dk}\alpha\rho)\, p_d - (\gamma_c\varepsilon_{dc} - \gamma_d\omega_{dz}\zeta\rho - \gamma_d\omega_{dk}\alpha\rho)\, p_c \\ &+ \gamma_d\omega_{dz}\bar{z} \;+\; \gamma_d\omega_{dk}\bar{k}\,. \end{aligned} \tag{13}$$

In this expression ε_{ij} denotes the elasticity of excess demand for good *i* with respect to the price or quantity of *j*, e.g. $\varepsilon_{dd} = H_d(P_d/Y_d)$. If final goods are normal, $\varepsilon_{dd}<0$ and $\varepsilon_{dc}>0$. The other new parameters, ω_{ij}, are elasticities of the supply of good *i* with respect to price or quantity *j*, e.g. $\omega_{dz} = G_{dz}(Z/Y_d) = (\partial Y_d/\partial Z_z)(Z/Y_d)$. Factor *K* is not used in production of good *D*, so $\omega_{dk}<0$. The sign of ω_{dz} depends on the relative land-intensity of production in the two agricultural sectors; we assume the soil-conserving crop to be less land-intensive, so $\omega_{dz}<0$.

Finally we note that for the traded goods, trade taxes T_j (here, a tariff for good *m*, export tax for good *x*) may be introduced, causing domestic prices to differ from world prices:

$$P_m = P_m^x(1+T_m) \qquad \text{and} \qquad P_x = P_X^W/(1+T_x).$$

In percentage change form:

$$p_m = p_m^W + (1+t_m) \qquad \text{and} \qquad p_x = p_X^W - (1+t_X). \tag{14}$$

Substituting from (14) into (11) and (13) and solving for y and p_d enables us to assess the general equilibrium welfare effects of policy changes as well as of exogenous changes in world prices of traded goods, under a range of assumptions about the economy's agricultural trade position and about on-site and off-site impacts of changes in land use.[13] Suppose soil-conserving crops to be exportable perennials (e.g., coffee, cocoa, oil palm, rubber, mango), and the erosive crops to be cereals grown in upland and sloping areas (e.g., rice, corn, cassava, millet), or in some cases exportable cash crops such as groundnut. Then there are three cases of interest in developing economies: the erosive crop is imported, not traded, or exported.[14] Algebraic solutions are provided in the Appendix; table 1 presents some illustrative numerical examples using the following parameter values: $\gamma_d = 0.1$; $\gamma_c = 0.15$; $\mu_c = -0.5$; $\delta_z = 0.2$; $\delta_k = 0.15$; $\varepsilon_{dd} = -0.1$; $\varepsilon_{dc} = 0.1$; $\omega_{dz} = -0.1$; $\omega_{dk} = -0.1$; $D = 0.1$; and $\rho = 1$. The welfare impact of each shock is compared under four alternative assumptions about land degradation: free disposal, on-site damage only; off-site damage only; and both damages together. On-site and off-site impacts are restricted to 10% and 5% respectively of the magnitude of the change in agricultural land allocation between erosive and soil-conserving sectors, i.e. $\zeta = -0.10$ and $\alpha = -0.05$.

The results in table 1 show for plausible parameter values that accounting for land degradation costs can alter significantly the measured welfare impact of a trade policy change, terms of trade shift or of factor endowment growth. In the first row, the measured welfare loss from imposition of an import tariff on the erosive crop with free disposal is only one-half to two-thirds that observed when on-site and off-site damages are valued. The second example reiterates the point made earlier in this paper that when a positive terms of trade shock raises the price of an exportable erosive crop, the value of increased environmental damage may diminish or even outweigh foreign currency gains. Given our choice of parameter values, an increase in P_d^w actually reduces welfare when both on-site and off-site effects are taken into account.

In the third case D is not traded, and two types of effect are at work. First, an exogenous price or endowment change alters the sectoral allocation of resources so as to equate the marginal value products of intersectorally mobile factors such as land. This supply-side effect increases or reduces the production of D accordingly. Second, the exogenous shocks alter total income, and this generates demand shifts that alter the equilibrium price and production of the non-traded crop. In the absence of these demand shifts each shock examined in the third case would cause output of D to decline, and therefore reduce land degradation. When the relative price of D adjusts endogenously, this result still holds weakly for the terms of trade shock, but factor endowment growth causes D output to rise, thereby increasing land degradation.

The results in table 1 are purely illustrative, and the experiences of individual countries of course depend on their characteristics. Nevertheless, for reasonable assumptions about sector size and factor intensity, the results seem well within the range of land degradation costs reported in Barbier and Bishop (1995). This underscores the importance of accounting for intersectoral relationships in assessing the economic impact of land degradation in developing countries.

Technical progress and the value of soil-conserving investments

Our initial statement of the effective land area in equation (3) included the possibility of crop-specific technical progress, as well as that of soil-conserving investments or changes in technique. Until now we have ignored these in order to concentrate on price changes. The algebra of factor-neutral technical progress closely parallels that of a comparable price change. The effects of exogenous soil-conserving shift (a change in M) are also easy to derive. Again taking the total differential of (3), this time with respect to all variables, and converting to percentage change form, we obtain:

(15) $$z = \overline{z} + \phi m + \tau_d t_d + \tau_c t_c + \zeta\{\rho(p_d - p_c) + \sigma(t_d - t_c)\}.$$

in which ϕ, τ_d and τ_c are elasticities of land quality with respect to M, T_d, and T_c respectively and σ is the elasticity of R with respect to the ratio T_d/T_c. For constant technology, a soil-conserving increase in M is seen to be capable of compensating for land-degrading increases in Q if $m > \zeta\phi^{-1}\rho(p_d - p_c)$. Similarly, at constant prices the on-site land-degrading impact of technical progress in the erosive crop can be countered by soil-conserving changes as long as $\phi(m/t_d) + \tau_d > \zeta\sigma$. As was the case for price changes, the impact of soil-conserving investments depends on several parameters including the differential erosivity of crops (ζ), the efficacy of the soil-conserving technology (ϕ), and the extent to which price or technology changes induce land reallocation among crops (σ).

By a process exactly analogous to the derivation of results in table 1 we find that the welfare effects of general soil conservation measures (an increase in M) or of technical progress in the soil-conserving crop are likely to have positive welfare effects even under free disposal, and that these effects are larger if on-site or off-site erosion differentials between D and C are large. Technical progress in the erosive crop will not unambiguously increase welfare; only if it drives down the relative price of the erosive crop - thus causing land to be withdrawn from its production - is this form of technical progress likely to result in an aggregate welfare gain.

Does economic liberalization promote land degradation?

The foregoing analysis has sressed endogenous price effects as moderating or magnifying the value of erosion damage caused by exogenous shocks such as terms of trade changes, endowment growth or technical progress. In the great majority of developing countries, price, trade and exchange rate policies have historically had direct and indirect effects that discriminate against agriculture as a sector, and against export crops in particular (Krueger, Schiff and Valdes 1988). However, in the last decade trade liberalization and reform of exchange rate regimes have brought about major improvements in agricultural incentives in many countries. What are the possible implications of economic liberalization for land degradation?

A large, if informal literature has grown up around this question. The case for a 'win-win' outcome of faster economic growth together with reduced land degradation has rested on the observations that prevailing price policies discriminate in favor of relatively more erosive food crops and against relatively benign perennial export crops; that capital market interventions have denied affordable investment funds to farmers; and that overall slow growth and economic instability due to macroeconomic mismanagement and vulnerability to external shocks in developing countries have retarded growth of demand for environmental 'goods' and the resources to meet that demand (Repetto 1989; Cruz and Repetto 1992; Munasinghe and Cruz 1995). Critics have responded that market reforms alone, without accompanying changes to extend planning horizons and lower rates of time discount, may have adverse environmental impacts: "better farm prices now, if they work as intended, will encourage 'soil mining' for quick, big crops now" (Lipton 1987:209). More formal analyses have demonstrated the potential for increased environmental degradation if the opening of resource-intensive sectors to trade is not accompanied by reforms securing property rights in resources (Brander and Taylor 1994; Lopez and Niklitschek 1991).

Given the scope of economic liberalization, the question of whether reforms promote or retard land degradation in agriculture must clearly be addressed in a general equilibrium setting. Not to do so would be to focus on relative price shifts in isolation from what are frequently very large changes in other sectors and at the level of the macroeconomy. As a field of policy-oriented research, use of applied general equilibrium (AGE) models to study the land degradation impacts of trade policy and related reforms in is in its infancy. However, early results provide support for the complementarity of economic reform and reduced degradation (Coxhead and Shively 1995; Bandara and Coxhead 1995; Pearson and Munasinghe 1995).

In AGE models, the range of policies potentially affecting farmers' crop production and soil conservation decisions is much greater than in the farm-level or single-sector models. One implication of this is that there exists potential for policies addressing narrow political economy goals -- food self-sufficiency in developing countries, for example, or farm income supports in wealthy nations -- to have negative environmental impacts by inducing expansion of land-degrading crops. More positively, policy reforms that reduce distortions, promote efficient operation of rural financial markets, and make property rights enforceable should encourage conservation-oriented decision-making in agriculture. The positive aspect is that these reforms also serve (indeed, are directed primarily at) other desirable economic and political goals. There may be grounds to hope that economic liberalization will also reduce rates of land degradation in developing country agriculture.

V Conclusions

In this paper I have reviewed some methodological, empirical and policy issues in the economic analysis of agricultural land degradation. After an initial review of single-farm, partial equilibrium models, a general equilibrium framework was developed to examine the causes and economic consequences of land degradation in developing economies.

The past fifteen years has seen the development of theoretically rigorous neoclassical models of resource allocation, investment and land degradation in the context of a single farm or representative farm. Predictions based on these models about the effect of a rise in the price of a soil-eroding crop are found to be ambiguous when their more restrictive assumptions are relaxed. Choice of technology, endogenous investment in soil conservation, risk and missing markets are some of the factors contributing to this ambiguity.

An empirical literature has grown up from this modeling base, and points the way forward for single-farm methodologies by raising empirical questions about physical processes -- the rate of soil regeneration and the role of soil-conserving investments -- as well as economic relationships, especially those setting the market and institutional context in which farm decisions are made. Consistent with the conditions of agricultural decision-making in wealthy and developing countries alike, this literature increasingly identifies policies and policy-induced distortions as key components in the analysis of the causes of land degradation.

Concern with the economic context of agricultural land degradation has also begun to generate a new modeling approach in which agricultural resource allocation decisions and environmental outcomes, as well as input and commodity prices, are all endogenous elements of a larger economic system. AGE models capturing the economic and physical links between agriculture and other sectors appear to have particular importance for analysis of land degradation issues in developing countries. Key parameters of such models include sector size, factor intensity, contribution of earnings from land to total income, elasticity of land use change, and the on-site and off-site productivity impacts of erosive land uses.

Not every land degradation issue merits the use of a multisector or general equilibrium approach. The simple model presented above provides a 'back of the envelope' means to assess whether partial equilibrium assumptions are appropriate. If the erosive sector is very small in relation to GDP, for example, then the costs of constructing a more general model are unlikely to be merited. However, under other circumstances -- and in particular when an erosive crop is a major consumer good, or trade item, or employer of land and labor -- a single sector model may produce misleading predictions of the effects of price and policy reforms or technical progress.

The most important advantage of the general equilibrium approach is that it encourages a focus on aggregate welfare rather than farm profitability as the indicator of the economic effects of a given change. It captures off-site externalities that are uniformly ignored by single sector models. It subsumes the resource endowment constraints also missing from such models. It highlights tradeoffs between economic gains (for example, foreign exchange earnings) and the value of physical losses when expansion of a land-degrading crop is contemplated. It provides a basis for comparing private and social gains and losses and for reviewing alternative values of unknown parameters, such as the propensity of erosive land use to contribute to downstream damages.

The next challenge for this area of research will be to construct models capable of incorporating both sectoral breadth and microeconomic detail at the level of the farm. Particularly in developing countries, economy-wide models need to be capable of accounting for price variability as an endogenous component of the economic system. Farm-level and household models need to incorporate risk preferences and price and yield uncertainty in predictions of crop choice, technology adoption and investment behavior. Finally, too little is understood about the physical implications of induced agricultural changes. Progress on this front will require a commitment by economists to interdisciplinary research, working closely in the field with agronomists, hydrologists and other natural scientists to create the foundations for truly integrated modelling of economic and physical processes.

References

Anderson, J. R. and J. Thampapillai. 1990. "Soil conservation in developing countries: project and policy intervention". Washington, D.C.: World Bank. Agriculture and Rural Development Department, Policy and Research Series, Paper No. 8.

Bandara, J. S., and I. Coxhead, with A. H. Chisholm, A. Ekanayake and S. Jayasuriya. 1995. "Economic reforms and the environment in Sri Lanka: an exploratory CGE analysis". Melbourne, Australia: La Trobe University, School of Agriculture: Agricultural Economics Discussion Paper No. 27/95.

Barbier, E. B. 1990. "The farm-level economics of soil conservation: the uplands of Java". *Land Economics* 66(2), May., pp. 198-211.

Barbier, E. B., and J. T. Bishop. 1995. "Economic values and incentives affecting soil and water conservation in developing countries". *Journal of Soil and Water Conservation*, March-April. pp.133-137.

Barrett, S. 1991. "Optimal soil conservation and the reform of agricultural pricing policies". *Journal of Development Economics* 36(2), pp. 167-187.

Benson, B. L., and M. D. Faminow. 1990. "Integration of spatial markets". *American Journal of Agricultural Economics* 72, pp.49-62.

Blaikie, P. M. 1985. *The political economy of soil erosion in developing countries.* London and New York: Longman.

Blaikie, P. M., and H. Brookfield. 1987. *Land degradation and society*. London and New York: Methuen.

Brander, J. A., and M. S. Taylor. 1994. "International trade and open access renewable resources: the small open economy case". Mimeo, University of British Columbia.

Bromley, D. W. 1991. *Environment and Economy*. Oxford: Basil Blackwell.

Bunce, A.C. 1942. *The economics of soil conservation.* Ames, IA: Iowa State College Press.

Burt, O. R. 1981. "Farm level economics of soil conservation in the Palouse area of the Northwest". *American Journal of Agricultural Economics* 63(1), Feb., pp. 83-92.

Chisholm, A. 1992. "Australian agriculture: a sustainability story". *Australian Journal of Agricultural Economics* 36(1), April, pp. 1-30.

Ciriacy-Wantrup, S.V. 1968. *Resource conservation: economics and policies.* Berkeley, CA.: University of California Press (3rd edition).

Clarke, H.R. 1992. "The supply of non-degraded agricultural land". *Australian Journal of Agricultural Economics* 36(1), April, pp. 31-56.

Coxhead, I., and S. K. Jayasuriya. 1994. "Technical change in agriculture and land degradation in developing countries: a general equilibrium analysis". *Land Economics* 70(1), February, pp. 20-37.

Coxhead, I., and S. K. Jayasuriya. 1995. "Tax and trade policies and the environment: the economics of soil erosion in developing countries". *American Journal of Agricultural Economics*, November (in press).

Coxhead, I., and Shively, G. 1995. "Measuring the environmental impacts of economic change: the case of land degradation in Philippine agriculture". University of Wisconsin-Madison, Department of Agricultural Economics, Staff Paper Series No.384, June.

Cruz, W., and R. Repetto. 1992. *The environmental effects of stabilization and structural adjustment programs: the Philippines case*. Washington, DC: World Resources Institute.

Dixit, A., and V. Norman. 1980. *Theory Of International Trade.* Cambridge, U.K.: Cambridge University Press.

Hoang, P. T. 1994. "Costs and benefits of terraces for erosion control: a case study of upland vegetable farmers in Atok, Benguet, Northern Luzon, Philippines". M.S. thesis, University of Wisconsin-Madison, Department of Agricultural Economics.

Krueger, A. O., M. Schiff, and A. Valdes. 1988. "Agricultural incentives in developing countries: measuring the effect of sectoral and economywide policies" *World Bank Economic Review* 2(3).

LaFrance, J. T. 1992. "Do increased commodity prices lead to more or less soil degradation?". *Australian Journal of Agricultural Economics* 36(1), April, pp. 57-82.

Lal, R. 1990. *Soil erosion in the tropics: principles and management.* New York: McGraw-Hill.

Lipton, M. 1987. "Limits of price policy for agriculture: which way now for the World Bank?". *Development Policy Review* 5, pp. 197-215.

Lopez, R. and Niklitschek, M. 1991. "Dual economic growth in poor tropical areas". *Journal of Development Economics* 36, pp. 189-211.

McConnell, K. E. 1983. "An economic model of soil conservation". *American Journal of Agricultural Economics* , Feb., pp. 83-89.

Minifie, Jim. 1994. “Some notes on the optimal control of soil erosion”. Bundoora: La Trobe University, School of Agriculture (typescript).

Munasinghe, M., and W. Cruz. 1995. *Economywide policies and the environment: lessons from experience*. Washington, D.C.: World Bank Environment Paper No. 10.

Pearson, A., and M. Munasinghe. 1995. "Natural resource management and economywide policies in Costa Rica: a computable general equilibrium (CGE) modeling approach". *World Bank Economic Review,* 9(2), May. pp. 259-286.

Perrings, C. 1989. "An optimal path to extinction? poverty and resource degradation in the open agrarian economy". *Journal of Development Economics* 30, pp. 1-24.

Pimentel, D., *et al.*. 1995. "Environmental and economic costs of soil erosion and conservation benefits." *Science*, vol. 367 (February), pp.1117-1123.

Pingali, P. 1991. "Agricultural growth and the environment: conditions for their compatibility in Asia's humid tropics". Los Banos, Philippines: International Rice Research Institute. Social Science Division Working Papers No. 91-12, September.

Rola, A., and P. Pingali. 1993. *Pesticides, rice productivity and farmers' health.: an economic assessment.* Los Banos, Philippines: International Rice Research Institute and World Resources Institute.

Repetto, R. 1989. "Economic incentives for sustainable production", Ch. 6 in G. Schramm and J. J. Warford (eds.): *Environmental management and economic development.* Baltimore, Md.: Johns Hopkins University Press for the World Bank: pp. 69-86.

Ribaudo, M. O. 1989. *Water quality benefits from the Conservation Reserve Program.* U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 606.

Sen, A.K. 1981. *Poverty and famines: an essay on entitlement and deprivation.* Oxford: Clarendon Press.

Shively, G. E. 1996. “Land degradation, soil conservation, and risk: evidence from a dynamic model of upland Philippine agriculture”. Madison, Wisconsin: University of Wisconsin Department of Agricultural Economics (PhD. dissertation).

Singh, I.; L. Squire and J. Strauss (editors). 1986. *Agricultural household models: extensions, applications, and policy.* Baltimore : Johns Hopkins University Press.

Southgate, D. 1988. "The economics of land degradation in the third world". Washington, D.C.: World Bank Environment Department, Working Paper No. 2, May.

TSC and WRI (Tropical Science Center and World Resources Institute). 1991. *Accounts overdue: natural resource depreciation in Costa Rica*. San Jose, Costa Rica, and Washington, D.C.: Tropical Science Center and World Resources Institute.

Walker, D. J. 1982. "A damage function to evaluate erosion control economics". *American Journal of Agricultural Economics* 64, pp. 690-698.

Walker, D.J., and Young, D. L. 1986. "The effect of technical progress on erosion damage and economic incentives for soil conservation " *Land Economics.* 62(1), pp..83-93.

World Bank. 1989. *Philippines natural resource management study*. Washington, DC: The World Bank.

World Bank. 1990. *Indonesia: sustainable development of forests, land, and water*. Washington, DC: The World Bank.

Table 1: Simulated welfare impacts of trade policy and terms of trade shocks (% changes)

	Free disposal	On-site only	Off-site only	On-site & off-site
On-site land degradation:	$\zeta = 0$	$\zeta = -0.1$	$\zeta = 0$	$\zeta = -0.1$
Off-site erosion damage:	$\alpha = 0$	$\alpha = 0$	$\alpha = -0.05$	$\alpha = -0.05$
1. *D* importable ($\mu_d = 0.25$)				
25% import tariff on *D*	–0.63	–1.13	–0.81	–1.31
2. D exportable ($\mu_d = -0.25$)				
25% world price rise of *D*	0.63	0.13	0.44	–0.06
3. D non-traded ($\mu_d = 0$)				
25% rise in world price of *C*	1.88	1.94	1.90	1.99
10% increase in $\overline{Z}$	2.00	1.54	1.80	1.42
10% increase in $\overline{K}$	1.50	1.12	1.33	1.02

Appendix

1. Derivation of equations (7) and (10).

Take the total differential of (3), holding technology and management variables fixed:

$$dZ = Ad\bar{Z} + \bar{Z}\,\mathrm{Ar}R_Q dQ, \text{ where } dQ = P_c^{-2}(P_c d\,P_d - P_d\, dP_c).$$

Multiply the first term on the r.h.s. by $\bar{Z}/\bar{Z}$ and the second term by Q/Q, then divide through by Z: Divide the second expression by $Q = P_d/P_c$ and combine to obtain:

$$\begin{aligned} z &= dZ/Z = (A\bar{Z}/Z)\bar{z} + (A\bar{Z}/Z)A_r(R/A)R_Q(Q/R)_Q. \\ &= \bar{z} + \rho\zeta(p_d - p_c) \end{aligned}$$

by definitions given in the text. The derivation of (10) from (9) follows an analogous procedure.

2. Derivation of equation (13).

Definitions of the ε_{dj} parameters make use of the fact that for the non-traded good, domestic demand and supply quantities are equal in equilibrium, i.e. $Q_d = Y_d$. In addition, we choose units so that initially $P_c = P_X = Y = 1$, so that $Y_j = \gamma_j$ for $j=c,d$. Signs of the ω_{dj} elasticities follow from the Rybzcinski Theorem in a specific-factor context (Dixit and Norman 1980:55).

3. Derivation of comparative static results in table 1.

The results for D importable and exportable are obtained directly from (11). When D is nontradable (i.e. when its price is endogenous), results are obtained by simultaneous solution of (11) and (13). Using Cramers's rule, solve:

$$\begin{bmatrix} 1 & -\rho(\delta_z\zeta + \delta_k\alpha) \\ D & \gamma_d(\varepsilon_{dd} - \rho(\omega_{dz}\zeta + \omega_{dk}\alpha)) \end{bmatrix} \begin{bmatrix} y \\ p_d \end{bmatrix} = \begin{bmatrix} -(\gamma_c\mu_c + \rho(\delta_z\zeta + \delta_k\alpha))p_c + \delta_z\bar{z} + \delta_k\bar{k} \\ -(\gamma_c\varepsilon_{dc} + \gamma_d\rho(\omega_{dz}\zeta + \omega_{dk}\alpha))p_c + \gamma_d\omega_{dz}\bar{z} + \gamma_d\omega_{dk}\bar{k} \end{bmatrix}$$

The determinant of the coefficient matrix is $\Gamma = \gamma_d(\varepsilon_{dd} - \rho(\omega_{dz}\zeta + \omega_{dk}\alpha)) + D(\delta_z\zeta + \delta_k\alpha)\rho$, which is negative given the factor intensity assumptions stated in the text. Comparative static results for a change in p_c are as follows:

(a) Free disposal ($\zeta = \alpha = 0$):

$$y/p_c = -\Gamma^{-1}(\gamma_c\gamma_d\mu_c\varepsilon_{dd}) > 0.$$

(b) On-site and off-site effects ($\zeta<0$, $\alpha<0$):

$$y/p_c = -\Gamma^{-1}\{\gamma_c\gamma_d\mu_c\varepsilon_{dd} + \rho(\delta_z\zeta + \delta_k\alpha)(\gamma_d\varepsilon_{dd} + \gamma_c\varepsilon_{dc})$$
$$+ \rho(\omega_{dz}\zeta + \omega_{dk}\alpha)\gamma_c\mu_c + \rho^2(\omega_{dz}\zeta + \omega_{dk}\alpha)(\delta_z\zeta + \delta_k\alpha)(1 - \gamma_d\}.$$

An expansion shows every term positive in this expression but one, $-\Gamma^{-1}\rho(\delta_z\zeta + \delta_k\alpha)\gamma_c\varepsilon_{dc} < 0$. In this term ε_{dc} captures the effect of substitution in consumption from C to D when the relative price of C increases. This substitution bids up P_d, and the supply response thus induced contributes to an increase in on-site and off-site erosion damages.

Results for changes in the factor endowments $\bar{z}$ and $\bar{k}$ are obtained by analogous methods.

---

[1] Department of Agricultural and Applied Economics, University of Wisconsin-Madison, Madison, WI 53706 USA. Research for this paper was supported by funding from USAID through the Sustainable Agriculture, Natural Resources and Environmental Management Collaborative Research Support Program (SANREM CRSP). I would like to thank Bill Provencher and an anonymous referee for very helpful comments on an earlier draft; remaining ; responsibility for all remaining errors is mine.

[2] The terms 'soil erosion' and 'land degradation' are sometimes assigned distinct meanings, with the former referring primarily to physical removal of soil through erosive practices, and the latter to deterioration of *in situ* soil quality through nutrient leaching, compaction, etc., caused in part by physical soil losses. The terms are used interchangeably in this paper, with the understanding that 'soil erosion' may carry the more limited meaning in particular contexts.

[3] Rather than measure the time path of soil depth or soil quality, Walker measures crop yield as an increasing function of topsoil depth; continued use of the erosive practice reduces future yields.

[4] According to McConnell, "other things equal, output expansion per farm in a given time period requires more soil loss. For example, output can be increased by cultivating land with greater slope, increasing soil loss" (p.84). This characterization of soil loss as a decision rather than a state variable creates analytical problems, for example the need to define substitution relationships between this and other inputs (Clarke 1992; Minifie 1994).

[5] See for example Walker and Young 1986; Barbier 1990; and Barrett 1991.

[6] It is symbolic of changing perceptions of land degradation that while the structure of McConnell's 1983 model allowed for soil quality improvements, his analysis did not pursue this possibility.

[7] The view represented by Clark parallels a similar shift by resource economists in other fields in which the issue of reinvestment has become relevant, for example fisheries restocking programs and the use of surface water to recharge aquifers.

[8] Walker's assertion that a higher output price will unambiguously favor more erosive agricultural practices (p.693) is erroneous. He defines the present value of the difference in a stream of net returns between adoption of the soil-conserving technique in year $t + 1$ and adoption in year t by δ_t . Inspection of his eq. (4) shows that $\partial\delta_t/\partial P$ (the differential NPV effect of a price rise) is unambiguously positive, as asserted in the text, only when future differences in net returns are ignored. The result could easily be reversed if use of the erosive technique in year t has a strongly negative impact on future yields, so that the difference in discounted future net returns outweighs the revenue gain in year 1.

[9] There is, however, a vigorous literature on the environmental impacts of long-term irrigated rice monoculture (Pingali 1991), as well as on the environmental implications of intensive fertilizer and chemical application in rice (Rola and Pingali 1993).

[10] Of course, this comparative static result need not hold in a dynamic or intertemporal model.

[11] See the Appendix for details.

[12] The selection of D as the non-traded good has no analytical significance (all price changes are relative in real models) but corresponds reasonably well to a stylization of developing economies in which trade in staple food crops (mainly annuals) is tightly restricted, while non-food crops (more frequently perennials) are grown mainly for export.

[13] The analysis as presented ignores revenue effects of existing taxes and tariffs. Under some circumstances their inclusion could change the predicted welfare effects of exogenous shocks. For a complete analysis see Coxhead and Jayasuriya 1995.

[14] The first case approximates the agricultural trade position of some economies of Sub-Saharan Africa; the second parts of monsoon Asia; the third a small group of cereals exporters (e.g., Thailand, Vietnam).