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Multiple equilibria, soil conservation investments, and the resilience of agricultural systems

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ABSTRACT. This paper provides a new explanation for the persistent land degradation in some parts of the world, despite the availability of seemingly effective soil conservation technologies. We demonstrate that soil conservation technologies may induce agricultural systems to exhibit equilibria characterized by both low and high levels of soil degradation. These two equilibria are separated by a threshold level of soil degradation beyond which a conservation investment will not yield a positive return. Once a parcel of land crosses this productivity threshold, soil degradation becomes economically irreversible (it is not profitable to invest in soil conservation) even though the degradation may be technically reversible. A case study of terracing investments in Peru is used to demonstrate the existence of multiple equilibria under conditions typical of many marginal agricultural areas. These findings help explain why attempts to encourage permanent adoption of soil conservation practices often fail, and how more successful policies could be designed.

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1. Introduction

Soil degradation has long been recognized as a key factor in the low and declining levels of agricultural productivity observed in some parts of the developing world (Lynam *et al.*, 1998; Scherr, 1999). In some highly fragile environments, found most often in the tropics, soils may be highly vulnerable to rapid and irreversible degradation with inappropriate agricultural practices. In these cases, there are arguably two equilibria, one with a relatively high level of productivity and another with a relatively low level of productivity. The most visible example of this is when steeply sloped land is cleared for agricultural use, making it vulnerable to extreme erosion and gully formation. Other less visible examples exist as well, for example when highly fertile volcanic ash soils are cleared for agricultural use. If these soils are allowed to dry out completely, say due to a drought, the soil structure and clay mineralogy can change irreversibly such that its productivity reduces significantly (e.g., Veldkamp, 1994).[1]

A great deal of research effort has been devoted to developing soil conservation technologies that allow farmers to maintain or enhance agricultural productivity by preventing soil degradation. As the preceding examples suggest, these technologies enhance the resilience of agricultural systems, i.e. they increase the system's ability to remain in one stability domain (say, one in which agricultural productivity can be sustained) when subjected to shocks or perturbations before switching to another domain (say, one in which agricultural productivity is not sustainable) (Holling, 1973; Perrings and Stern, 2000).

Situations in which soil degradation is rapid and irreversible are relatively rare, however. In most cases, soil degradation is relatively slow, occurring over multiple growing seasons, e.g. through gradual topsoil loss from rainfall or nutrient mining by growing crops without sufficient use of fertilizers and incorporation of organic matter into the soil. This more gradual form of soil degradation is manageable and reversible in most cases. Topsoil loss can be prevented by various practices, such as contour plowing and construction of terraces; nutrients and soil organic matter can be returned to the soil by use of both organic and mineral fertilizers. In this more typical situation, where soil degradation is physically reversible, it might be argued that an agricultural system is characterized by a unique global equilibrium, and one might conclude that soil conservation practices do not affect the resilience of agricultural systems in the same sense that they do when soil degradation is irreversible.

Data from throughout the world show that in many cases where substantial soil degradation has occurred, farmers choose not to adopt soil conservation practices that could restore agricultural productivity to a higher level. Consequently, soil degradation remains a serious threat to agricultural productivity, particularly in the tropics (Oldeman *et al.*, 1990; Koning and Smaling, 2005). Many explanations for this situation have been offered in the literature. Most of these explanations have to do with

[1] With some extremely fragile soils it may not be possible to sustain a high level productivity under any agricultural use, in which case one could argue that there is a single, low-productivity equilibrium.

institutional and economic failures that constrain farmers' knowledge about soil conservation or limit the incentives to invest in soil conservation (Lutz *et al*., 1994; Heath and Binswanger, 1996; Scherr, 1999).

In this paper, using the concepts of multiple equilibria and resilience, we provide a new explanation for persistent agricultural soil degradation, despite the availability of seemingly effective soil conservation technologies. We show that along the path of productivity decline associated with soil degradation, the returns to investments in soil conservation increase to a maximum value and decline thereafter. In the case where the returns are first positive but become negative beyond some point, two equilibria exist: a high-productivity equilibrium in which a soil conservation technology is adopted, and a low-level equilibrium in which a soil conservation technology is not adopted. These equilibria are separated by a threshold level of soil degradation, defined as the point at which returns to the soil conservation investment become negative. This analysis shows that once soil degradation occurs beyond the threshold separating the two equilibria, it may be physically reversible but economically irreversible, in the sense that a rational farmer would not invest in restoring the lost soil productivity. This concept of economic irreversibility is closely related to the economic literature on irreversible investment (Pindyck, 1991), ecosystem–economic interactions (Kahn and O'Neill, 1999) and restoration of natural resources (Zhao and Zilberman, 1999).

This paper begins with a discussion of properties of tropical soils and how these properties relate to the concept of resilience. Next we present a simple model of a soil conservation investment, and use this model to provide a heuristic explanation for the existence of multiple equilibria in agricultural systems. We then demonstrate the existence of multiple equilibria using a case study of terracing investments in Peru. The paper concludes with a discussion of policy implications.

2. Tropical soils and the resilience of agricultural systems

Tropical soils differentiate themselves mainly through the rate of various soil-forming processes associated with specific climatic conditions. As a result of high temperatures, high precipitation, and age, extremely weathered and leached soils with a low inherent soil fertility are often found in the tropics. The high rate of soil forming processes also increases vulnerability to soil degradation, which can take place at a high rate (e.g. Lal *et al*., 1997). Human activity is also an important driving factor behind soil formation that may have either positive or negative effects on soil productivity. On the one hand, soil fertility can be improved with the application of fertilizers and organic matter. On the other hand, soils can be degraded through nutrient depletion, pollution, and compaction. As we show below, this vulnerability of tropical soils to degradation can cause productivity to decline to the point that restorative investments in soil conservation technologies may not be profitable.

In most developing countries, soil degradation is prevalent, as shown by Oldeman *et al*. (1990) in their global assessment of soil conditions. The rate and degree of soil degradation depends on both soil properties, such as soil organic matter content, that affect its resistance to degradation and on the land management practices that the farmer uses. Mining of soil resources is often associated with resource-poor farmers, apparently because they are not willing or able to make long-term investments to maintain the soil quality (Shepherd and Soule, 1998).

Soil degradation is usually a reversible process. Typical examples are the traditional slash and burn systems where soil fertility is extracted for several seasons, after which the soil is left fallow for an extended period and soil fertility is restored. However, soil degradation is irreversible in some cases. Examples of permanent changes that have adverse productivity effects are the drying of volcanic ash soils, the oxidation of acid-sulphate soils, and the complete removal of topsoil by extreme rainfall events.

In this analysis, we follow the approach proposed by Droogers and Bouma (1997) in which a soil is defined in terms of a set of stable characteristics (e.g. origin, soil depth, percent clay) that are a function of the soil's pedogenetic history (e.g. parent material) and a set of dynamic properties (soil depth, nutrient and organic matter content, water holding capacity) that depend on both the stable characteristics and on land use history (the sequence of past crops grown and the associated management decisions, such as fertilization and tillage). Crop productivity in turn depends on these soil properties, as well as on climate, genetic properties of the crop, and current management by the farmer. We define the following variables: a vector $\mathbf{c}$ of stable soil characteristics; a vector $\mathbf{h}$ of land use history (representing lagged values of crop choice, management, and soil properties); a vector $\boldsymbol{z}$ of actual soil properties; a vector of climate variables ε; crop genetic factors $\boldsymbol{g}$ and management $\boldsymbol{x}$. Crop productivity potential can be expressed in general terms by the production function[2]

$$y = f(\mathbf{x},\ \mathbf{z}(\mathbf{c}, \mathbf{h}),\ \mathbf{g}, \boldsymbol{\varepsilon}). \tag{1}$$

Crop growth models developed by agricultural scientists incorporate these variables in a set of interrelated processes that link soil properties, climate, and management to crop productivity (e.g. Tsuji *et al.*, 1994).

A basic feature of crop production functions are the relationships between the physical environment and plant growth. Given the genetic characteristics of the crop, a plant will grow and produce a positive crop output when soil properties and climatic conditions are within certain bounds. For each soil property, a technically optimal value exists at which yield is maximized, *ceteris paribus*, with yield non-increasing as the characteristic deviates from the technical optimum and eventually reaching zero. Often crop production functions exhibit a von Liebig-type response, with a threshold value above which there is a plateau with little response and below which productivity declines rapidly. For example, the potato production function shows this behavior in the deep volcanic soils of the Ecuadorian Andes, where topsoil depth has little impact on crop yield until it reaches a critical value, beyond which productivity declines rapidly towards zero (Antle and Stoorvogel, 2006).

[2] For further discussion of this model, see Antle and Stoorvogel (2001).

Using this model, soil degradation can be defined as any process that changes soil properties in ways that lower productivity. For example, soil erosion reduces topsoil depth, reduces available nutrients and water, and thus lowers crop productivity. Soil conservation practices prevent the productivity losses associated with erosion. Conservation investments, such as terraces, can capture topsoil being transported downhill by water erosion, and thus can increase topsoil depth on terraced fields and restore lost productivity.

3. Soil conservation investments and multiple equilibria

In this section we develop a conceptual model of soil conservation investments, such as terraces, ridge tillage, filter strips, and agroforestry, following Antle *et al.* (2005). This model utilizes the production function described in the previous section that relates soil properties to productivity. Following Stoorvogel *et al.* (2004) we define *inherent productivity* as the productivity attainable at a site (i.e. a parcel of land managed as a unit, such as a farmer's field) with a specified set of bio-physical conditions (soils, topography, micro-climate) and a standard set of management practices. Intuitively, inherent productivity represents what an experienced farmer would know about the productivity potential of a parcel of land. Across the landscape, inherent productivity represents the spatial variation in productivity associated with spatial variation in soils and climate conditions.

Let the inherent productivity at a site indicated by the variable INP_{ist} for crop i at site s in period t. Using the production function described in the preceding section (equation (1)), we define $\mathbf{x_0}$ as a standard set of management practices (fertilizer application, tillage, irrigation, etc.). The inherent productivity at a site s in period t is defined as $INP_{ist} = f(\mathbf{x_0}, \mathbf{z}_{ist}, \mathbf{g}, \boldsymbol{\varepsilon}_{ist})$. Based on this definition, inherent productivity can be estimated with bio-physical crop simulations models, executed with site-specific soils and climate data and a standard set of management practices.

Generally, soil conservation investments may have three types of effects on productivity. First, some conservation investments may enhance the productivity of an un-degraded field. This 'augmentation effect' could occur, for example, by increasing organic matter contents in low fertility soils. Following figure 1, a terrace would have an augmentation effect if it were built in a field at time t_1 and the field's inherent productivity increased over time along the path *I*.

More typical is a situation in which a field is initially cultivated without the use of conservation practices, soil productivity declines over time, and at some later point in time conservation practices may be introduced. Without the use of conservation practices, the field's soil productivity would eventually decline to a new, low-level equilibrium (path II in figure 1). Another possibility is that conservation practices are adopted on an un-degraded field at time t_0 and productivity is maintained at the initial level INP_1. In this case, we shall say that the conservation investment has an *avoidance effect* by preventing the productivity decline that otherwise would have occurred. However, if a terrace were built at a later time $t_2 > t_1$ when productivity had declined to INP_2, and then part or all of the lost productivity was restored, we shall say the terrace has a *restoration* *effect* (paths III, IV and V). When the investment is made at a time such as t_2 before the land is fully degraded, there will typically be both an avoidance effect (preventing productivity from falling from INP_2 to INP_3) and a restoration effect (raising productivity to some level above INP_2). If it is not possible to fully restore productivity to the level of the un-degraded soil, the productivity with a mature terrace will be at a level $INP_4 < INP_1$. If the investment has the potential to augment productivity, then the mature terrace might achieve a level of productivity greater than was possible with un-degraded soils, e.g. $INP_5 > INP_1$.

An implication of the preceding discussion is that the effects of a soil conservation investment on productivity depend on the initial conditions of the system, i.e. the state of soil productivity at the site at the time the investment is made. This initial condition determines the type of effect that the conservation investment has. Note, in particular, that three distinct possibilities exist:

1. If a field were un-degraded at the time a conservation investment was made, then the benefits of the investment would be a pure avoidance effect.
2. If a field were fully degraded at the time a conservation investment was made, then the benefits of the investment would be a pure restoration effect.
3. If a field were partially degraded at the time a conservation investment was made, then the benefits of the investment would be a combination of an avoidance effect and a restoration effect.

As we shall show below, the possibility of multiple equilibria arises from the fact that a conservation investment may not be profitable from the avoidance effect or the restoration effect alone, but may be profitable when the two effects are combined.

3.1 Existence of multiple equilibria

In this section we use a simple linear approximation to the productivity effects of terraces in the model presented above to provide a heuristic explanation for the existence of multiple equilibria in soil conservation investment problems. In the following section we confirm the intuition of this heuristic analysis with an empirical example and provide some evidence of the empirical significance of multiple equilibria.

The problem addressed here is whether or not to invest in soil conservation at each site s, assuming the farmer makes this decision under different intial soil conditions. The economically rational farmer will choose to invest in a capital asset such as a terrace or other soil conservation technology if the expected NPV of the production system with the investment is higher than the expected NPV without the investment. Define $NPV(i,s,\Delta t,\tau), i = N,C$, as the returns to the conventional technology (N) and the conservation technology (C) at site s, calculated over time interval Δt, at point τ in time. The farmer will make the investment if and only if $\Delta NPV(N,C,s,\Delta t,\tau) = NPV(C,s,\Delta t,\tau) - NPV(N,s,\Delta t,\tau) > 0$. If $\Delta NPV < 0$ the farmer does not make the investment, production continues at the site, and at time $\tau + 1$ the farmer again assesses whether or not to make a soil

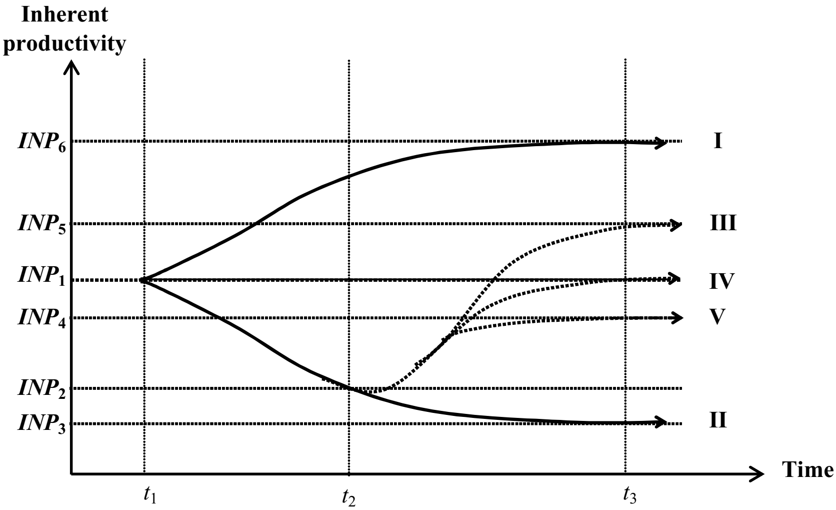

Figure 1. *Modeling the effects of conservation investments on productivity: the augmentation, avoidance, and restoration effects*
Source: Antle *et al.* (2005).

conservation investment. Note that with certainty and perfect foresight, the optimal time for the investment will be the point τ^* where $\Delta NPV(\tau^*) > 0$ and $\Delta NPV(\tau^*) > \Delta NPV(\tau)$ for all τ. With uncertainty, the optimal timing of the investment could involve risk aversion as well as option values (Fisher and Krutilla, 1985).

To demonstrate the existence of multiple equilibria in this type of problem, we make some simplifying assumptions. First, we assume that each field has a unique initial inherent productivity associated with the bio-physical conditions at that site. Therefore, each field can be thought of as starting at a different point along a path like II in figure 1. Second, we set $\Delta t = t_3 - t_1$ so that farmers are always looking Δt time periods into the future at each point in time. Third, we assume that the paths such as II and IV in figure 1 are linear and that the slope of the two paths are equal, as shown in figure 2. Thus, in figure 2, starting at time t_1 with productivity INP_1, a farmer who does not invest in a soil conservation technology sees productivity follow the path ABDF over time, declining eventually to level INP_3. If the farmer decides to invest at some point t_2 such that $t_1 < t_2 < t_3$, productivity follows a path such as ABCE. If the farmer were to invest at time t_3, then productivity follows the path ABDG.

To prove that multiple equilibria may exist, we need to derive the behavior of ΔNPV as we change the initial conditions of the investment problem (the inherent productivity of the soil). For this purpose we can compare three cases represented in figure 2. First, consider the case of choosing to invest when productivity is at level INP_1. In this case, there is only an avoidance effect that can be measured in terms of cumulative productivity as the area between the lines AC and AD over the interval

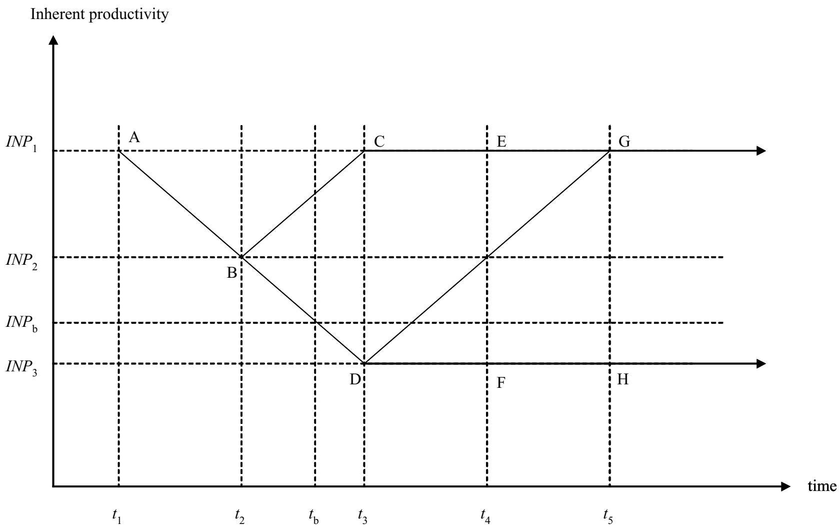

Figure 2. *Inherent productivity paths without and with terracing*

(t_1,t_3), i.e. the triangle ACD. Second, consider the case of choosing to invest when productivity is initially at the level INP_3 (i.e. after the soil is completely degraded) with the farmer basing decisions on the productivity path between t_3 and t_5. In this case, there is a restoration effect equal to the area between lines DG and DH, i.e. the triange DGH. Thus, by the geometry of the figure, it is obvious that the avoidance effect ACD is equal to the restoration effect DGH. Third, consider the case of choosing to invest at time t_2 half way between t_1 and t_3. In this case, there is both an avoidance effect and a restoration effect. By the geometry of the problem, it is easy to see that the the combined avoidance and restoration effects of this third case is the area BCEFD and is therefore 50 per cent greater than the pure avoidance effect ACD or the pure restoration effect (DGH).

The implication of the previous paragraph is that ΔNPV follows a pattern illustrated in figure 3 (note, however, that ΔNPV is measured in different units than *INP*). By the geometry of figure 2, the relationship in figure 3 will be concave downwards with a unique maximum. This analysis suggests the possible existence of multiple equilibria, as demonstrated by the following three cases:

Case 1: The farmer always invests. By the construction of this example, $\Delta NPV(t_1) = \Delta NPV(t_3)$; hence, if $\Delta NPV(t_1) > 0$, then $\Delta NPV(t) > 0$ for all t. Therefore, the rational farmer will invest at some point in time. Because the terrace is profitable at t_1, it might be argued that the investment would be made at that time. However, a farmer with foresight might know that returns would be higher at some later time and would delay investing until then.

Case 2: The farmer never invests. Another possibility is that $\Delta NPV < 0$ for all times along the path ABDF, hence, the farmer would choose not to

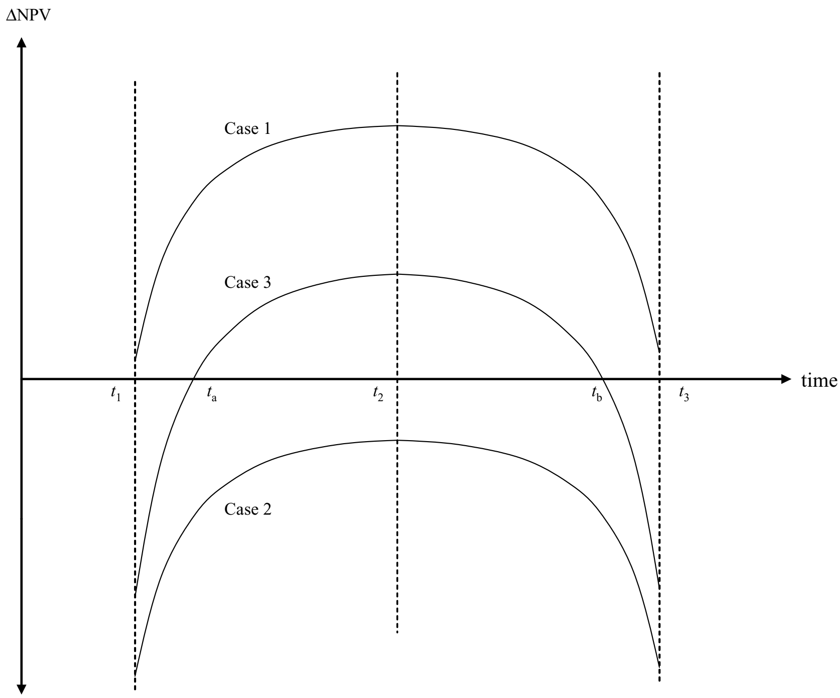

Figure 3. *NPV changes associated with Case 1 (the farmer always invests), Case 2 (the farmer never invests), and Case 3 (investment depends on initial conditions)*

invest in a conservation technology. Note that, in this example, $\Delta NPV(t)$ achieves its maximum at t_2; hence this case corresponds to the situation where $\Delta NPV(t_2) < 0$.

Case 3: The farmer's investment choice depends on the initial conditions. This is the case that provides the possibility of multiple equilibria. Starting at point A in figure 2, suppose that $\Delta NPV(t_1) < 0$, but that it becomes positive along the path between points A and D, so that $\Delta NPV(t_2) > 0$. As noted earlier, under the assumptions made for figure 2, the productivity effect of the investment made at point A is equal to the the effect at point D, hence $\Delta NPV(t_1) = \Delta NPV(t_3) < 0$. Therefore, there exist points $t_1 < t_a < t_b < t_3$ and corresponding productivity levels INP_a and INP_b such that $\Delta NPV(t_a) = \Delta NPV(t_b) = 0$ and $\Delta NPV(t) > 0$ for $t_a < t < t_b$ (see figure 3). It follows that any land unit with initial productivity greater than INP_b will have $\Delta NPV > 0$ at some point in time and therefore the farmer will invest in a terrace. However, any land unit with initial productivity less than INP_b will have $\Delta NPV < 0$ at all times and therefore the farmer will never invest.

Finally, we note that by the symmetry of the productivity paths AD and DG (Case 3), it can be shown that, if a farmer were to invest at t_3, ΔNPV would follow the same pattern as starting at t_1. However, without some change in the system, returns to investment are negative at t_3 and the farmer has no incentive to invest. Once productivity has fallen below INP_b, some change in or shock to the system would be needed to increase productivity enough to make the investment profitable. One way this could happen would be for a governmental or non-governmental organization to provide the farmer with a financial incentive to invest, as has been done in many development projects. If such incentives were provided for a long enough time for productivity to rise above the threshold where the investment is profitable, then it would become economically sustainable without further subsidization. We elaborate on the policy implications of this analysis in the concluding section.

4. Evidence from a case study of terrace investments in Peru

In this section, we utilize a model from a case study of terrace investments in Peru (Antle *et al.*, 2005) to provide empirical support to the analysis in the previous section. This study utilized data collected in the La Encañada watershed in the Cajamarca region of northern Peru. This region is characterized by three agro-ecological zones: the valley floors, the lower hillsides, and the upper hillsides. We focus our analysis on the steeply sloped lower-hillside region, where cropland is the principal land use and the average slope exceeds 25 per cent. Erosion is a major threat to the productivity on the shallow soils. About one-third of the cropland in the watershed has been terraced, in part due to subsidies provided by the Peruvian government and non-governmental entities.

The productivity dynamics of figure 1 will now be incorporated into a model for the economic assessment of returns to investments in soil conservation technologies. Farmers are assumed to choose land use and inputs to maximize expected net returns on each land unit they manage. Expected net returns for activity i (crop, fallow, other land use) at site s in period t are defined as

$$NR_{ist} = p_{ist}q_{ist} - C_{ist}$$

where:

$q_{ist} = q_{ist}(p_{ist}, \mathbf{w}_{ist}, INP_{ist}) =$ quantity supplied of output i
$p_{ist} =$ expected price of output i
$C_{ist} = \sum_j w_{ijst}\, v_{ijst} =$ variable cost function
$v_{ijst} = v_{ij}(p_{ist}, \mathbf{w}_{ist}, INP_{ist}) =$ quantity demanded of input j
$w_{ijst} =$ price of input j for output i, $\mathbf{w}_{ist}$ is the corresponding vector
$INP_{ist} =$ inherent productivity of activity i

The output quantities supplied and input quantities demanded are derived from a static single-period expected profit maximization, where input decisions are made at the beginning of the crop cycle, given previous land use, input prices and expected output prices.

In each crop cycle, the farmer chooses the activity at site s to maximize expected returns by solving

$$NR_{st} = \max_{\{\delta_{ist}\}} \sum\nolimits_i \delta_{ist} NR_{ist}$$

where $\delta_{ist} = 1$ if activity i is chosen and $\delta_{ist} = 0$ otherwise. We define the economic value of a production system k at site s as the net present value

$$NPV_{ks} = \sum_{i=1}^{T} D_t(NR_{st} - CM_{kst}) - FC_{ks}$$

where:

$T =$ number of decision periods in the planning horizon
$D_t = (1/(1+r))^t =$ discount rate with interest rate r per decision period
$CM_{kst} =$ conservation investment maintenance cost
$FC_{ks} =$ conservation investment fixed cost.

An econometric process simulation model of the production system was used to implement the analysis (Valdivia, 2002; Antle *et al.*, 2005). This model is based on the specification and estimation of output supply and input demand equations for each activity (potatoes and tubers, cereals, legumes, and pasture). These econometric models are estimated using the inherent productivity data derived from corresponding bio-physical crop models as inputs to represent spatial variation in productivity. These models are then used as the basis for the construction of a simulation model that characterizes, for each field, the choice of land use in each growing season (crop, pasture, or fallow), and the management (variable input use) for the selected activity in each season.

Productivity dynamics in a farmer's field depend on bio-physical conditions (soil depth, soil organic matter, etc.) and these conditions are in turn partly dependent on management (crop choice, tillage, fertilizer applications, etc.). In principle, bio-physical models, such as the DSSAT crop models (Tsuji *et al.*, 1994) could be used to estimate the productivity dynamics of a crop production system over time, if the changes in soil properties that occurred over time were known. Alternatively, more complex agro-ecosystem models, such as EPIC (Williams *et al.*, 1983) or Century (Parton *et al.*, 1994), that jointly simulate crop growth and soil processes, could be used. However, these more complex models involve a large number of parameters – data that often are not available on a site-specific basis. Another limitation is that existing bio-physical models were not developed to represent soil processes in terraced systems. Therefore, there is a knowledge gap in the literature regarding the dynamics of crop productivity under terraced conditions.

Given this gap in the bio-physical science literature, in this analysis we implement a simpler modeling approach that allows us to utilize data from the scientific literature and field measurements (e.g. field slope, top soil depth, soil organic matter) that are related to bio-physical processes together with *a priori* assumptions about the relationship between slope and terrace productivity, and then subject these assumptions to sensitivity analysis. To implement this approach, we make two key assumptions. First, we assume that there is a monotonic increasing productivity path from the time the investment is made to the time when the investment matures (i.e. when its full productivity potential is realized). Second, we assume that there is a monotonic relationship between field slope and the productivity potential of terraces. If slope is changed due to a terrace, it will reduce soil erosion by water, provide more moisture retention for crop use, and make it easier to work the soil.

As illustrated in figure 1, the productivity potential of a terrace depends on the augmentation, restoration, and avoidance effects. To model these relationships, we define the maximum amount of productivity that can be gained from a terrace ($AT_{\max} \geq 100$) or lost through erosion ($0 \leq AE_{\max} \leq 100$) relative to a base value of 100. For a site with a field slope of $SLOPE_s \leq 100$ per cent, we define the total site-specific productivity change from terracing and from erosion as

$$AT_s = (100 + (AT_{\max} - 100) \cdot (SLOPE_s/100)^{\alpha})/100$$
$$AE_s = (100 + (100 - AE_{\max}) \cdot (SLOPEs/100)^{\beta})/100,$$

where α and β are positive parameters between zero and one. We assume that the path between the initial productivity level and the final productivity level is linear, as in figure 2. Thus, given a base value of inherent productivity of INP_{is0}, the inherent productivity at time t on an unterraced field is given by $INP_{ist} = (t/T) \cdot (AE_s - 1) \cdot INP_{is0}$, and inherent productivity on a terraced field is given by $INP_{ist} = (t/T) \cdot (AE_s - 1) \cdot INP_{is0}$.

To investigate the potential for multiple equilibria, the production model with terraces was simulated for 1,000 fields randomly sampled from the La Encañada region. Antle *et al.* (2005) show that, under a set of plausible assumptions about key bio-physical and economic variables (e.g. field slope, terrace productivity, discount rates), the proportion of fields where terraces are profitable can range from as low as 10 per cent to as high as 90 per cent. Simulations were run for a set of scenarios that represent different levels of terrace investment subsidy, and also for scenarios representing different bio-physical conditions (low and high field slope) and location (low altitude and high altitude) that affect terrace productivity. The simulations were initiated at points t_1, t_2 and t_3 as defined in figures 2 and 3, with points 1 and 3 separated by 20 growing seasons (ten years).

Figure 4 shows the results of the simulations in the format of figure 3. The figure shows the average change in *NPV* for terrace adoption plotted for the full sample of 1,000 fields, as well as for fields corresponding to low and high slope groups and low and high altitude groups. Figure 4 confirms the hypothesized relationships of figure 3, and shows that all three cases identified in figure 3 exist in the La Encañada watershed.

Table 1 summarizes the data for all of the scenarios that were simulated. In the base case (no subsidies, all slopes and altitudes), about 29 per cent of fields have multiple equilibria (Case 3), whereas about 31 per cent of the fields correspond to Case 1 (terraces always profitable) and about 24 per cent correspond to Case 2 (terraces never profitable). These results are case specific, but suggest that multiple equilibria do exist in a marginal

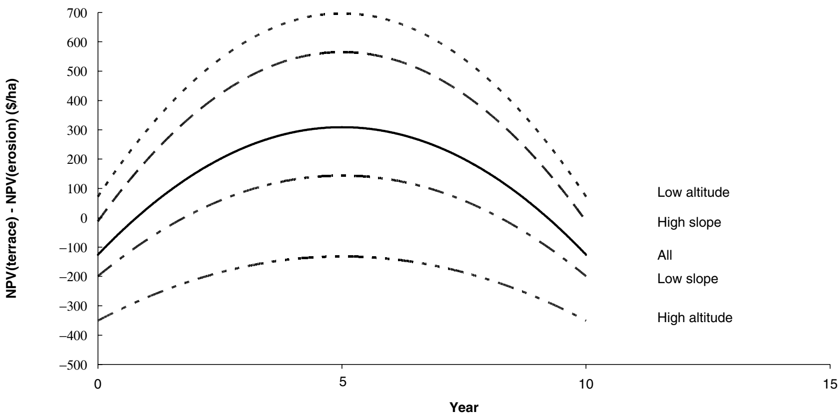

Figure 4. *Average simulated difference in NPV for adoption of terraces, for all fields, for low and high slope, and for low and high altitude fields, La Encañada watershed, Cajamarca, Peru*

Table 1. *Percent of sites with multiple equilibria for terrace investments, La Encañada watershed, Cajamarca, Peru*

Scenario	*Case 1*	*Case 2*	*Case 3*
Base	31	40	29
Low subsidy*	50	19	31
High subsidy**	82	5	13
Low altitude	58	11	31
High altitude	0	74	26
Low slope	22	50	28
High slope	44	24	32

Notes: *75 per cent subsidy of investment cost.
**75 per cent subsidy of investment plus maintenance costs.
Case 1 = always invest.
Case 2 = never invest.
Case 3 = multiple equilibria.

agricultural system that is typical of conditions seen in various parts of the world. Figure 4 and Table 1 show that subsidies reduce the proportion of cases where multiple equilibria occur, because the profitability of the investment is higher with a subsidy. When both investment and maintenance subsidies are available, the simulations show that over 80 per cent of the terraces are profitable, and the likelihood of multiple equilibria is substantially reduced. Table 1 also shows that the likelihood of multiple equilibria is fairly stable across bio-physical conditions and location. The proportion of Cases 1 (always profitable) and 2 (never profitable) varies substantially across slope and altitude. At high altitude, where productivity is low, there are no sites where terrace investments are always profitable. Terraces are profitable on 44 per cent of highly sloped fields, twice as often as on fields with low slopes.

5. Conclusions and policy implications

In this paper we have shown through both heuristic argument and an empirical example that production systems with conservation investments may exhibit multiple equilibria. This result will apply to any situation where an investment can be made that prevents the loss of productivity and restores lost productivity, a feature typical of soil conservation investments.

This analysis leads to the conclusion that the resilience of agricultural systems is likely to be highly variable, depending on a combination of bio-physical and economic conditions. In a world in which economically feasible conservation technologies are available to well-informed farmers with access to well-functioning product, input, and credit markets, systems are resilient in the sense that most farmers will make profitable soil conservation investments before land resources became highly degraded. Under these conditions – arguably approximated by the situation in much of the industrialized world – the phenomenon of multiple equilibria is not likely to be very important. However, the possibility of multiple equilibria and economic irreversibility is more likely to be important in developing countries, because their agricultural systems are far less resilient and because economic and institutional conditions are not favorable to farmers making conservation investments that could prevent high levels of degradation. Therefore, the likelihood that farmers may degrade soils beyond the threshold point where conservation investments are profitable is much higher.

The possibility of multiple equilibria and economically irreversible soil degradation has several notable policy implications. First, subsidies for adoption of conservation investments can reduce the likelihood that irreversible degradation will occur, but there may be a high cost to prevention of economically irreversible degradation. Whether or not this cost should be borne by society requires assessing both the private and social benefits and costs of soil degradation. As our simulation results show, offering farmers subsidies to construct terraces could reduce the number of fields where multiple equilibria – and thus economically irreversible degradation – could occur. But our case study suggests that a high level of subsidization may be required to eliminate this possibility, and under current and foreseeable conditions in many regions of the developing world neither subsidies nor other actions needed to prevent high levels of degradation are likely to be feasible.

Second, the timing and duration of policies to support adoption of soil conservation practices is important in preventing soil degradation and restoring lost soil productivity. Moreover, our analysis suggests that soil conservation policies or programs, as typically implemented, are unlikely to lead to the permanent adoption of soil conservation practices once soils become highly degraded. Our analysis shows that once farmers have degraded soils to the point that the system is operating in the low-productivity domain, a subsidy to encourage adoption of soil conservation practices will have to be maintained long enough for soil productivity to be restored to the point that the system returns to the high-productivity domain. Due to the site-specific character of soil degradation and its relation to soil productivity, the time required to return a system from one equilibrium to another is likely to be highly variable. Therefore, soil conservation projects of a short, fixed duration may not succeed in restoring most sites to the equilibrium where a high level of productivity is sustainable. The farther is the degradation below the threshold separating the two equilibria, and the slower is the rate at which soil productivity can be restored, the longer will subsidies have to be maintained to successfully restore the system to the high-productivity equilibrium.

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