THE ECONOMICS OF TERRACES IN THE PERUVIAN ANDES: AN APPLICATION OF SENSITIVITY ANALYSIS IN AN INTEGRATED ASSESSMENT MODEL

by

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of the requirements for the degree

of

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I dedicate this thesis to my wife Ana, for her love, support, encouragement, and for being the joy of my life.

I also dedicate this thesis to my family, my parents Roberto and Elsa, my sister, Carla, and my brother, Enrique, for their love and continued support.

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ABSTRACT

Land degradation is a global constraint to economic development in countries such as Peru that have a complex topography where soil erosion is an important problem. Governmental and private institutions are promoting adoption of soil conservation practices such as construction of slow formation terraces, yet they lack accurate estimates of the private and social benefits and costs of these investments. The objective of this thesis is to provide a better understanding of the economics of terrace investments by (1) developing a method to conduct a sensitivity analysis of an integrated assessment model designed for the agricultural production systems in Peru, and (2) conducting an economic analysis of the effects of terraces on productivity and their economic implications. The Tradeoff Analysis software was used to implement an integrated assessment model and to conduct a sensitivity analysis of terrace investments in a watershed in northern Peru. Key parameters in the analysis are: erosion and terrace effects on productivity; interest rates; terrace maintenance and investment costs; and time to achieve terrace maturity. The analysis shows that the proportion of fields on which terraces are a profitable investment can be highly sensitive to key parameters, thus demonstrating the importance of sensitivity analysis to understand and interpret policy implications derived from integrated assessment models. The analysis also verifies the hypothesis that physical and economic heterogeneity are important determinants of terrace profitability. Terraces were found to be most profitable on more steeply sloped fields, implying that farmers have incentives to invest in terraces where both private and social returns are the highest.

CHAPTER 1

INTRODUCTION

Background

The Andes hold a large number of peasant families for whom agriculture constitutes the main source of income. Crop production is difficult because of the extreme and variable weather conditions and frequent frost and drought (Valdivia et al. 1996).

Peru is a country with a relative scarcity of irrigated cropland at levels that are among the lowest in Latin America. Table 1 shows that in 1993 Peru had only 0.05 Ha of irrigated cropland per person; Argentina and Ecuador have a similar amount of irrigated cropland. However, Peru is the country with fewest hectares of cropland per capita.

Table 1: Cropland Per Capita in South American Countries

	CROPLAND					
SOUTH AMERICA Country	**Total Hectares (000) 1993**	**Hectares Per Capita 1993**	**Irrigated CroplandHa /Per 1993**	**Total Hectares (000) 1983**	**Hectares Per Capita 1983**	**Irrigated CroplandHa/Per 1983**
Guyana	496	0.61	0.15	495	0.63	0.16
Suriname	68	0.16	0.12	57	0.16	0.14
Chile	4257	0.31	0.09	4302	0.37	0.11
Ecuador	3020	0.28	0.06	2490	0.29	0.05
Argentina	27200	0.81	0.05	27200	0.92	0.06
Peru	**3430**	**0.15**	**0.05**	**3650**	**0.2**	**0.07**
Uruguay	1304	0.41	0.02	1376	0.46	0.05
Bolivia	2380	0.34	0.02	2173	0.36	0.03
Paraguay	2270	0.48	0.01	1930	0.56	0.02
Colombia	5460	0.16	0.01	5249	0.19	0.02
Brazil	48955	0.31	0.01	51000	0.39	0.02
Venezuela	3915	0.19	0.01	3758	0.23	0.01

Source: Adapted from FAO (2002) and WRI (1997)

The heterogeneous topography of the country can explain the low number of irrigated hectares per person. Peru is divided into three ecological zones: coast, sierra and jungle. The coast is mostly desert, the jungle is a tropic humid zone with a very fragile ecology, and the sierra has a very mountainous topography. Most of the croplands and natural pastures are located in the sierra. The erosion caused by rain on these steeply sloped croplands is a significant problem.

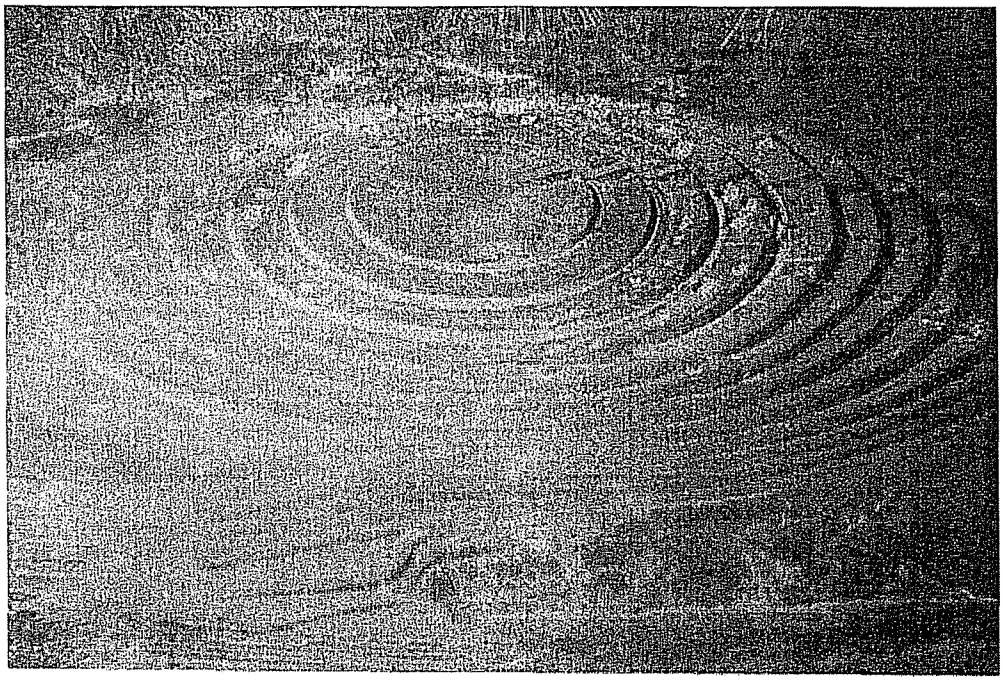
Ancient Peruvians solved the problem of erosion and low productivity by building terraces and irrigation channels. The purpose of the terraces was twofold: to increase crop production and to decrease the natural risk of production (by increasing water-holding capacity of the soil), and to decrease the erosion rate on these lands.

These ancient terraces have lasted until present days but the extent of terraced land has decreased (Gonzales et al. 1999). In recent years for regions where pre-Hispanic terraces do not exist, there has been an increase in public and private initiatives in terracing. PRONAMACHCS[1] is one of the institutions that is implementing different policies to rebuild and maintain old terraces and also to build new ones in zones with high rates of erosion. PRONAMACHCS seeks to bring part of the land that is in the watershed basins into integrated conservation and agroforestry management. To accomplish this, PRONAMACHCS is helping farmers to establish resource management committees and training them to adopt conservation practices, control pests, protect trees against damage by domestic animals, manage regrowth, and integrate environmentally

[1] PRONAMACHCS: Programa Nacional de Manejo de Cuencas Hidrograficas y Conservacion de Suelos (National Program for Hydrographic Watershed Management and Soil Conservation).

sound practices into both their farming and their forestry activities. In addition, the aim of this effort is to develop communal tree nurseries, produce seedlings, and plant trees.

Figure 1: Picture of Rebuilt Inca's Terraces.



Description of the Problem

The Peruvian Andes is a zone with high erosion damage. This loss of cropping soil contributes to the poverty of families. This study will address this issue in the Department of Cajamarca where 90% of its territory is occupied by the "Cordillera de los Andes" which contains many agro-ecological zones with varied agriculture and livestock potential. The average household plot in this department is less than 5 hectares and the production system is oriented to family-consumption (Gonzales et al. 1999). Farmers in

this region plant crops in places with steep slopes and where the loss of soil due to erosion reduces productivity.

La Encañada is a watershed within the Department of Cajamarca characterized by a variety of topographies where the level of erosion is particularly high. The slopes vary from 5% to more than 100% (note that 100% = 45 degrees). According to the U.S. Department of Agriculture the maximum slope recommended for planting crops is 21% (12 degrees approximately). In recent years, farmers have started working on different activities related to land conservation. Many private and government projects are encouraging farmers to participate in such activities. The most important activity in this zone is the construction of terraces.

Production systems are complex since farmers use a wide variety of inputs in their fields to grow one, two or more crops in the same field. Increasing the agricultural output of a given field may involve tradeoffs among yields, profits and/or environmental impacts. Policymakers such as PRONAMACHCS are seeking tools that help to understand the production system and thereby increase productivity and profitability in this region by promoting soil conservation practices such as the use of slow formation terraces. But the key question of whether terraces are profitable for farmers remains unresolved as well as the degree of adoption of such conservation practices and the off farm effects.

Most of the literature related to the profitability of terraces uses a simple cost-benefit approach at "representative" sites to determine whether terraces are profitable or not. However, to understand the economics of terraces in a spatially heterogeneous region

such as the Andes, more complex models are needed. There are several factors that can affect profitability of terraces. These factors need to be identified in order to determine how they affect productivity and what appropriate policies can be implemented. Discount rates, investment and maintenance costs, time to achieve full maturity of terraces, and erosion and terracing effects on productivity are some of the key parameters influencing the return to terraces.

Lutz et al. (1994) argues that returns to conservation depend on specific agroecological conditions faced, on the technologies used, and on prices of inputs used and outputs produced. Certainly, one of the most fundamental facts of agriculture is *heterogeneity*. Farmers are different because of their location, different discount rates, access to credit, physical features (e.g. soil characteristics and slope of their fields), levels of income (rich and poor farmers), etc. For instance, analyses of terrace investment must account for heterogeneity to generate correctly targeted policies. If heterogeneity is not accounted for the analysis, it can lead to incorrect conclusions about the economic value of terraces and other conservation practices (Antle and Stoorvogel 2001).

Economically rational farmers will adopt soil conservation if it is profitable for them. Lutz et al. (1994), argue that farmer's investment decisions are based on consideration of benefits and costs. Generally, Lutz et al., argue that economic (i.e. techno-economic factors such as material interventions applied to restore individual plots, tools used, etc.) and other non-economic factors (i.e. organizational factors, such as land tenure, land access rules, farmers organizations, and etc.; ideational factors, such as farmers' perceptions and belief system) may influence farmers' decisions. In this study,

maximization of economic returns is assumed, while recognizing that other factors may also influence decisions. A justification for this approach is the fact that economic models predict behavior well.

From the social point of view, investment in conservation practices such as slow formation terraces may reduce externalities associated with land degradation. Natural resources and environmental attributes such as water quality are valuable assets in that they yield flows of services to people. Public policies and the actions of individuals and farmers can lead to changes in the flow of these services, thereby creating benefits and costs.

Both economic theory and empirical observation show that when land degradation causes external costs such as water pollution, private individuals are likely to use practices that cause more erosion than what is socially optimal is to reduce agricultural productivity, but it also may affect those downstream by decreasing water availability and water quality. Although these externalities are important in analyzing the effects of terraces, it is not the aim of this thesis to study the off farm effects (externalities), (Valdivia 2000). However, the results from the economic analysis of terrace investments in this study provide the basis for a future study incorporating such externalities.

Understanding agricultural production is critical to developing economic production models for use in integrated assessment analysis. In this type of analysis, economic data are inputs into economic production models and soil and climate data are inputs into crop and livestock process models. The outputs of these process models may be used as inputs into economic and environmental models. The outcomes of both the

economic and crop process models can in turn be used to assess tradeoffs among economic and environmental outcomes at a regional scale (Antle, Capalbo, Crissman 1998). A disadvantage of these process models is that they often require many parameters and make assumptions regarding the functional form of the model. Thus, model results are conditional on the model structure, the choice of a functional form, and key exogenous parameters (Dawkins et al. 2001).

Users of these models need to know how sensitive model results are to underlying assumptions. In the analysis of terraces the critical issue is the sensitivity of terrace profitability to these assumptions. Careful assessment of simulation models must be made. For example, the Intergovernmental Panel on Climate Change (IPCC 2001) concludes in its assessment of climate change, "...that the results of existing agricultural impact studies must be assigned a low degree of confidence. How uncertain these results are has not been quantified. The implication is that econometrics and integrated assessment modelers need to undertake sensitivity analysis to determine key assumptions and parameters and focus quantitative uncertainty analysis on those dimensions of the models."

Objectives

The objective of this study is to provide a better understanding of the economics of terrace investments in an important region of Peru. Furthermore, this study is intended to determine whether returns to terracing investments are profitable or not by providing an economic analysis of the effects of terracing on productivity and the effects of some

policies such as subsidies. Critical parameters that affect returns to terracing will be identified in order to conduct a sensitivity analysis.

To accomplish this, this study will: (1) develop a method to conduct sensitivity analysis of an integrated assessment model designed for the agricultural production systems in Peru; and (2) to conduct an economic analysis of the effects of terraces on productivity. This analysis will use a loosely coupled modeling system, which links econometric and biophysical models to generate the tradeoffs among yields, profits and/or environmental impacts. This system is further evaluated by presenting a method for sensitivity analysis of the main parameters and their economic implications.

Use of the Results

Results from this thesis will provide a useful understanding of the economics of terraces investments and the important factors that affect returns to this investment. Results can be used by researchers to implement soil conservation projects. Results also provide a methodological approach to conduct sensitivity analysis when complex models are used and traditional approaches cannot be used. Policy makers can also use the results to establish appropriate policies (e.g. subsidies on investment and maintenance costs of terraces). Another contribution of this thesis is that it provides a broad discussion about the literature available on soil degradation, conservation practices, profitability and adoption of such conservation practices, in particular, for slow formation terraces. Finally, this thesis provides a good example of the use of the Tradeoff Analysis Model.

Although the on-farm productivity effects of erosion and terraces studied here are believed to be the most important effects, a complete examination of terrace investments would require broader analysis that would include possible externalities. This study provides the economic analysis that can serve as the foundation for a broader study that includes externalities.

CHAPTER 2

LITERATURE REVIEW

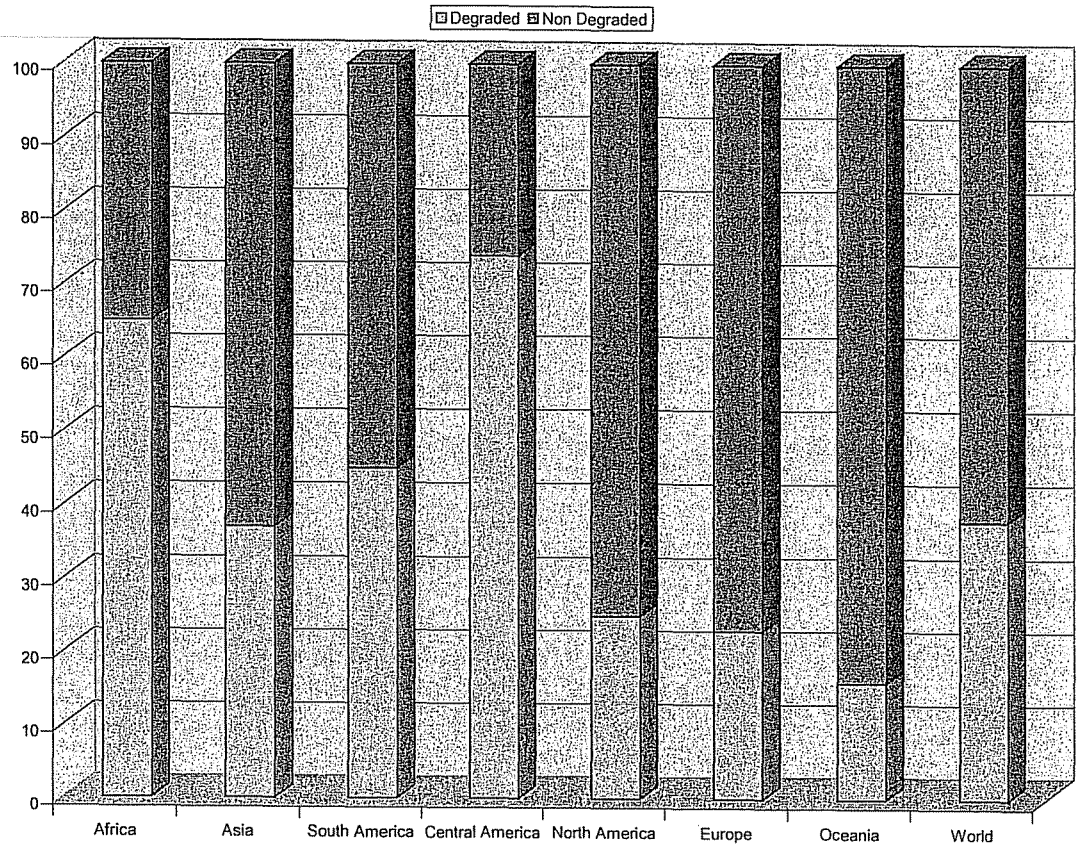
Land Degradation and Soil Erosion: Causes and Effects

Land degradation, including soil erosion, continues to be a global constraint to economic development. Despite decades of efforts to arrest land degradation, many farmers are reluctant or unable to adopt appropriate land-use practices. Often these practices fail to combine high productivity, increased soil fertility, reduced soil erosion and enhanced welfare. Still, soil conservation is proposed as a viable route to obtain these objectives (Ekbom 1998).

The negative changes in soil quality is a worldwide concern, especially in developing countries where land degradation is becoming a limiting factor in increasing or even sustaining agricultural production. Heerink et al. (2001) describe that according to the GLASOD[2] survey, 38% of the world's agricultural land is degraded, while in Africa and Central America, the share of degraded land in total agricultural land is as high as 65 and 74%, respectively. South America's agricultural degraded land is around 45% (see Figure 2).

[2] The Global Assessment of Soil Degradation project, based on a formal survey of more than 250 regional experts.

Figure 2: Global Estimates of Soil Degradation of Agricultural Land, by Region.



Source: Heerink et al. (2001).

Kruseman et al. (2001) defines the concept of soil degradation in order to evaluate different approaches for bio-economic models in which biophysical processes are linked to decision-making processes. They define soil in connection with agricultural use, as a "loose surface material of the earth, in which plant grows". Soil degradation has been defined qualitatively as the "state where the balance between attacking forces of climate and the natural resistance of the terrain against these forces has been broken, leading to decreased current and/or future capacity for supporting life". Kruseman et al. point out that soil degradation is associated with reductions in soil depth due to displacement of

soil material (erosion under the influence of wind and/or water) and changes in properties *in situ*, primarily changes in nutrients, soil organic matter and water holding capacity.

Kruseman et al. focus their analysis at the household level where the direct relationship between decision makers and physical processes take place. They point out that the key issue is the formulation of production functions that capture on one hand the interactions between biophysical processes and the environment, and on the other hand agricultural technology choice and allocation of production factors as dictated by economic factors. Two aspects are fundamental to their discussion: (i) the traditional relationship between inputs and yield, where the inputs include soil quality, and (ii) the relationship between agricultural management practices and soil quality. In this context, soil degradation can be viewed as both a *cause* of yield decline and an *effect* of agricultural practices.

According to Heerink et al., the main negative consequences of soil degradation are on-farm declines in crop production, off-farm damages from siltation of reservoirs and riverbeds, and the destruction of the environment. They also argue that the magnitude of on-farm effects of soil degradation is under dispute. Estimates of the annual rate of loss of agricultural land through degradation range from 0.3 to 1.0% of the world's arable land. The relation between soil degradation and yields is poorly documented, quantitative empirical work is scarce, and off-side effects of soil degradation are even more difficult to quantify.

Zimmerer (1993b) asserts that severe soil erosion in the Andes Mountains of South America constrains rural development and exacerbates poverty by undermining the

productive capacity of highland agriculture. His study focuses on the adoption of erosion-inducing practices by peasant farmers in the Bolivian Andes. His study's objective was to evaluate interrelated socio-economic, techno-managerial, and perceptual aspects of the causes of erosion and their implications for programs and policy promoting conservation-with-development. Zimmerer first examines the impact on local soil conservation of increased economic diversification involving non-farm activities by peasant farmers. Second, his study concerns the relation of soil erosion to technologies and land use practices in peasant farming. Third, his study concerns peasant farmers' perceptions and knowledge about soil erosion.

Zimmerer's study analyzes economic conditions that influence peasant farmers as they choose to alter, or alternatively maintain, production practices. He found that employment in non-farm work has led to labor shortages in peasant land use and, consequently, worsening soil erosion. Specific macroeconomic policies are found to have fueled these economic and environmental changes at the farm level. Also, Zimmerer's study shows that diminished labor availability in peasant production spurred erosion-inducing changes in farm technologies and practices in the Bolivian Andes. Finally, this study determines that land, rather than labor, is widely perceived as the chief resource-related cause of soil erosion, with implications for conservation with development.

Zimmerer explains that moderate and severe soil erosion cover, or at least threaten to cover, the majority of mountainous terrain in the major Andean countries where more than 10 million rural inhabitants reside.

Table 2: Estimates of Soil Erosion in the Andes.

Country	Area Extent	Erosion Rate
Colombia	Not available	48 tons/ha/yr (cited in Asby, 1985)
Ecuador	12% of country (Staver et.al.1991) 65% of country (cited in Posner 1982)	0-836 tons/ha/yr (Harden 1988) 82 tons/ha/yr (Reyes 1983)
Peru	50% of country (cited in Posner 1982)	10-70 tons/ha/yr (Low 1967)
Bolivia	80% of country (USAID in Godoy 1984) 35-41% of country (IIDE and USAID 1986)	114-173 tons/ha/yr (Zimmerer 1991)

Source: Zimmerer, Karl S. (1993).

Table 2 presents some estimates of erosion rates and area extent of the Andean countries. According to Zimmerer, these estimates are of limited accuracy, primarily because time and scale-dependent aspects of soil loss and sediment transfer make comprehensive measurement difficult. Uncertainty in the rate and extent of soil erosion in the Andes resembles the situation in the Himalayan Mountains of South Asia. In both the Andes and the Himalayan, additional uncertainty regarding soil erosion arises due to the role of natural versus anthropogenic soil erosion, the historical time frame of soil erosion, and the causes of anthropogenic soil erosion.

The anthropogenic origin of soil erosion in the Andes is emphasized in accounts dealing with the period of Spanish conquest and colonization in the 1500s and the 1600s. These accounts offer a significant contribution toward understanding human-related aspects of recent erosion. They introduce four conditions that are invoked in assessments

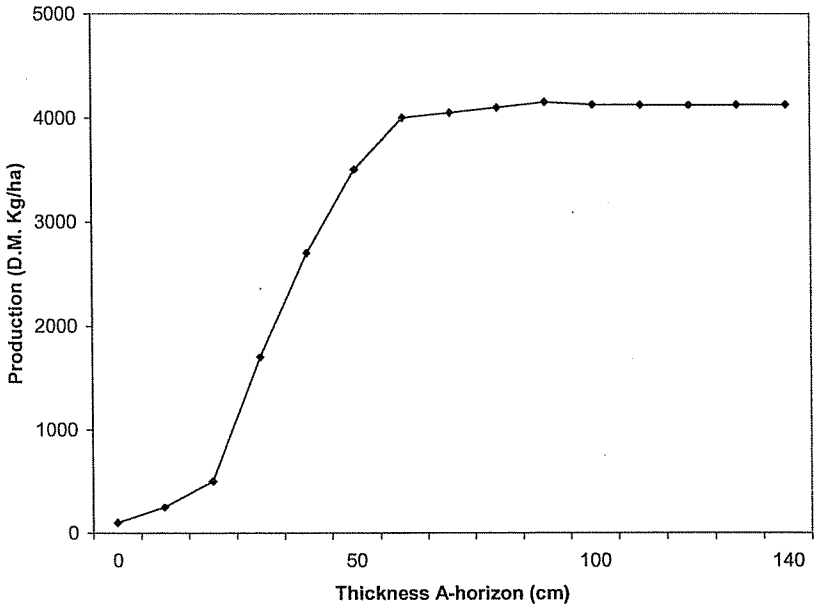
of the current erosion dilemma. The conditions and their proposed cause-and-effect scenarios for soil erosion in the early colonial period are:

- Human population: "demographic collapse" among Andean peoples due primarily to ravaging epidemics of Old World diseases led to abandonment of agricultural terraces and subsequent erosion.
- Political Economy: Tribute obligations for fuel and timber in the form of trees and shrubs, grasses, and even moss, turf and llama dung reduced vegetative cover and degraded soil structure, thus impelling erosion.
- Technology: Introduction of Old World technologies, crops, and livestock, which partly replaced indigenous technology, worsened erosion.
- Culture: Cultural change, particularly the alleged loss of both a conservation ethic and local indigenous knowledge about environmental management, contributed to an erosion crisis.

According to Antle and Stoorvogel (2001), soil quality is extremely difficult to define in general terms because it depends on soil use. They also argue that soil quality may have implications for environmental quality and that in many cases it can only be estimated by modeling the interaction of a number of land characteristics. Simulation models can be used to estimate the effects of changes in soil quality on productivity; for example, crop model results can be interpreted as an estimate of the inherent productivity of a site. One drawback of the simulation models is that they were developed under specific conditions, necessitating calibration and validation of these models when they are applied under different conditions. Antle and Stoorvogel also argue that changes in

soil quality can be highly site-specific, and that changes take place at the field and sub-field scale in response to land use and management practices.

Figure 3: The Effect of Thickness of the A-Horizon on the Dry Matter Production of Potatoes as Simulated with DSSAT.[3]



Source: Antle and Stoorvogel (2001).

Antle and Stoorvogel illustrate the specificity of changes in soil quality using a study from a production system of northern Ecuador where the use of tractors plowing on steep slopes causes the movement of topsoil. Under such conditions cultivation on steeply sloped hillsides mechanically transports soil down-slope causing the topsoil to be removed from the upper part of the field. Research estimates that 1.2% of the topsoil is completely removed by this process. As topsoil depth decreases, productivity declines

[3] DSSAT: Decision Support System for Agrotechnology Transfer. Crop growth simulation Model, Tsuji et al. (1994).

slowly at first, but beyond a critical depth productivity declines rapidly and approaches zero (see Figure 3).

Antle and Stoorvogel address the quantification of this type of site-specific change in soil conditions on productivity. Most models use an average of soil depth per field or per region to estimate productivity, showing little impact on total productivity. Antle and Stoovorgel's data suggest that the spatial variability in soils within fields or even sub-fields should be considered in order to detect this loss in productivity and obtain an accurate estimate of productivity and sustainability of production systems. In conclusion, they argue that in the analysis of the tradeoffs between policy and sustainability, the scale of analysis must be carefully considered. Model-based analysis at a regional scale may lead to the erroneous conclusion that mechanical erosion and other site-specific processes have little impact on the sustainability of a production system, whereas analysis conducted at the field or sub field scale and then aggregated to the regional level may result in a very different estimate of a system's sustainability.

Conservation Practices

According to Reining (1992), erosion control is geared towards the reduction of the kinetic energy of the raindrops before they reach the ground in order to diminish the surface runoff and to improve the stability of the soil. Soil conservation practices are artificial alterations of the land relief to control water, wind and tillage erosion.

Some of the most used conservation practices are detailed by Reining. Some of these are:

- Contouring: Cultivation of the soil along the terraces' contours. The preparation of transverse furrows with a light slope gradient of 1–2% helps to draw off the surface runoff while reducing soil loss. However, during heavy rainstorms contouring is not an effective erosion control measure.
- Strip Cropping: Cultivation of crops in alternating contour strips of different widths is more effective than contouring alone. Contour strips of crops which allow erosion are alternated on a slope with contour strips of crops which prevent erosion. As an alternative, contour strips of grass can be planted between strips of food crops.
- Conservation Tillage Practices: Farmers leave crop residues on the field to reduce wind and water erosion.
- Terraces: They are earth embankments, channels or combination of embankment and channels constructed across the slope to reduce the slope length at suitable spacing and with acceptable grades for one or more of the following purposes: to reduce soil erosion by water, to provide for maximum retention of moisture for crop use, to remove surface water at a non-erosive velocity, to improve topographic conditions and farmability, to reduce sediment content in runoff water, to reduce peak runoff rates to installations downstream, or to improve water quality. The most suitable features of a terrace depend mainly on the gradient, but are also dependent on the soil and rainfall conditions. Terraces make it possible to utilize steep areas

agriculturally. They may be used on relatively flat land in cases where soil and climate conditions are conducive to erosion.

According to Lutz et al. (1994b), land degradation is one major problem to the sustainability of agricultural production in Central America and the Caribbean. They assert that surprisingly little empirical analysis has been done on the causes and severity of land degradation problems and on how to address it. Many conservation programs have failed because farmers often have not adopted the recommended conservation practices or have abandoned them once the project ended. They investigated the nature and severity of the soil degradation problems and assessed the cost-effectiveness of the proposed solutions using a cost-benefit analysis. Their study focuses on the profitability of the measures and the deterrents to their adoption from the farmer's point of view.

Lutz et al. conclude that the profitability of conservation measures is an empirical and site-specific issue. Returns to conservation depend on the specific agro-ecological conditions faced, the technologies used, the prices of inputs, and the output revenue. Data remains a limitation despite several decades of soil conservation efforts. The payoff to additional research could be high if soil conservation would be more targeted toward concentration on areas with greatest need.

The results of the Lutz's case studies show that conservation is profitable in some cases but not in others. Except when high-value crops are planted on very fragile soils, expensive mechanical structures are unlikely to be profitable for the farmers. Conservation measures are likely to be profitable either when they are cheap and simple or when they allow farmers to adopt improved practices.

According to Lutz, farmers' decisions to invest in conservation practices are based on considerations of benefit and cost: they tend to adopt conservation measures when it is in their interest to do so, unless some constraint is present. Cases in which returns to conservation were estimated to be low or negative were strongly correlated with low adoption rates. They finally recommend an analysis of the role of the government toward conservation practices, its policies and effects on productivity.

Terraces, Characteristics and Costs

Agricultural terraces are among the most distinctive and widespread features of the Andean highland landscape. In the pre-Hispanic era, terraces built by indigenous societies supported large populations, primarily in the arid valleys of western Andes, but also on the moist eastern Andean flanks (Treacey 1989). The Inca's terraces supported production, research, and erosion control. Terrace design depended on the importance of these three purposes. Terraces show variation in the width, height and type of the walls, drainage, accessibility, etc. Almost all terraces had an irrigation system (de Vries 1986).

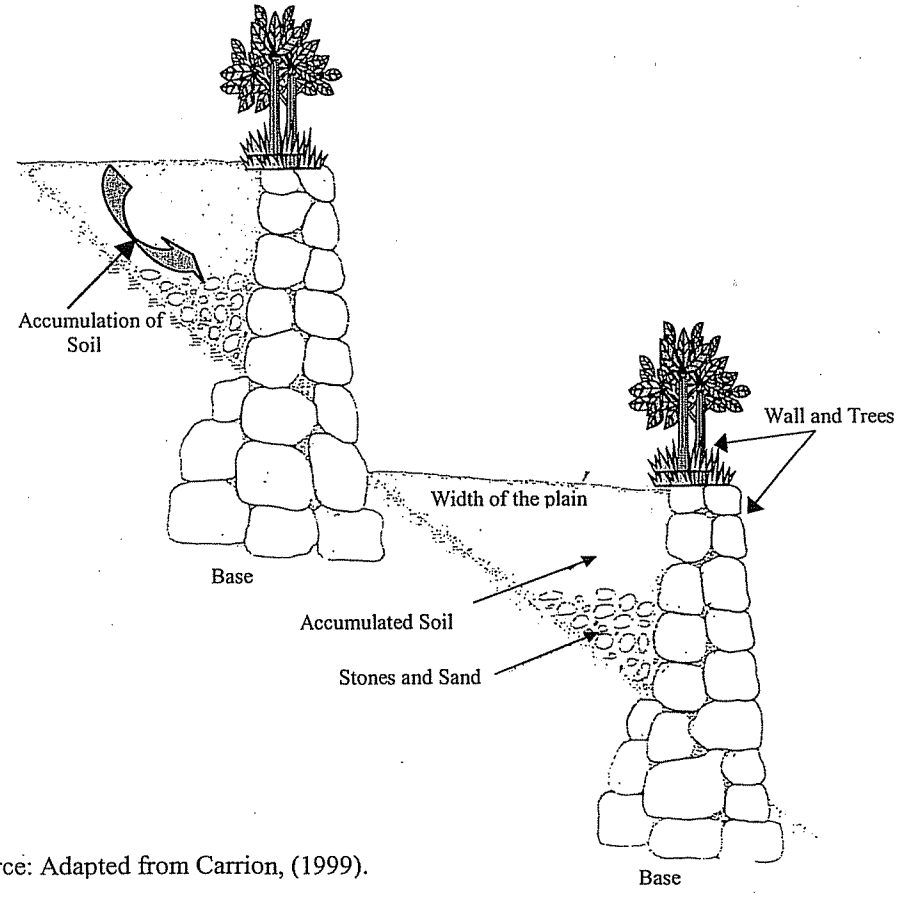
Vasquez (1997) defines terraces as a set of layers built as the steps on a stairway. The National Institute of Natural Resources of Peru (INRENA) describes terraces made of stone walls in such a way that the slope is modified (see Figure 4).

Terraces have four main functions (Gonzales de Olarte 1999):

1. Improve the natural conditions for production.
2. Decrease the rate of erosion.
3. Increase soil moisture.
4. Generate positive environmental externalities.

One widespread soil conservation practices in the Andes is the construction of slow formation terraces. These terraces are a combination of infiltration ditches, walls and live barriers (e.g. trees). Pereira (2000) suggests establishing live barriers in the contour of the hillside (e.g. rows of trees or continuous bands of vegetation). The slow formation terraces will decrease the superficial water run-off, increasing water infiltration and intercepting the soil sediment; this process of accumulation of soil will form the terraces (UNESCO-ROSTLAC 1997).

Figure 4: Structure of Slow Formation Terraces.



Source: Adapted from Carrion, (1999).

Treacey (1989) argues that once built, the annual costs to maintain terraces are minimal and may be accomplished with family labor, or with assistance acquired through

reciprocal labor exchange networks or hired workers.[4] He also argues that construction or reconstruction costs are labor costs, since few tools other than picks and shovels are needed. Work may be accomplished in a piecemeal fashion by family labor or by massing labor to rebuild entire ranks of terraces. Labor measurements indicate two men can rebuild 7.2m² of wall in one day[5]. Assuming a common size terrace wall measures 1.8m high and 50m in length, two men could restore an entire terrace in two weeks, or build an entirely new one in a slightly longer period of time. He compared labor data from results obtained from different projects in Peru (see Table 3).

Table 3: Per Hectare Labor Requirements for Terrace Reconstruction in Peruvian Villages.

Project	Worker Days/Ha		Source
Puno	3750	(a)	Coolman, 1985:45
Coporaque (Colca Valley)	2000		Treacey, 1987:55
Lari (Colca Valley)	1320	(b)	Guillet, 1987:412
Cajamarca	800-1000		Araujo, 1986:283
PNCSACH	336-1181	(c)	PNCSACH, 1984:88
Puno (Asillo)	622	(d)	Ramos, 1986: 236
Porcon (Cajamarca)	500	(e)	Araujo, 1986:283
San Pedro de Casta (Lima)	350	(f)	Masson, 1986:213

(a) Average of over 30 sites in the Department of Puno
(b) Extrapolated from farmers' calculations, not measured directly
(c) Range of values from 12 areas in highlands
(d) Reported total costs per hectare of US$ 1121.0
(e) Reported total costs per hectare of US$ 468.0
(f) Reported total costs per hectare of US$ 1162.0
Source: Treacey (1989).

Rist et al. (1991) conducted a study in the Andes of Bolivia where they estimate the labor cost associated to the construction of terraces. They argue that the average labor

[4] The area of study of his research was the Valley of Colca, Peru. Most of his estimates are referred to this zone.
[5] Treacey assumes 1 day equals 6 hours of work.

cost is about Bs.6427/Ha (US$2,380.00), and an average of 1285 "jornales"[6] are needed to build 1 hectare of terraces (see Table 4).

Table 4: Labor Cost for the Construction of Terraces, Tapacari, Bolivia, 1990.

Field Number	Labor/Ha (Jornal)	Labor Cost/Jornal (US$)	Total Labor Cost/Ha (US$)
1	1364	1.85	2525.93
2	1270	1.85	2351.85
3	1000	1.85	1851.85
4	1379	1.85	2553.70
5	1320	1.85	2444.44
6	1379	1.85	2553.70
Average	**1285.33**	**1.85**	**2380.25**

Source: Adapted from Rist et al. (1991).

Effects of Terraces on Productivity

B. Gebremedhim et al. (1999) conducted a study in Tigray, Ethiopia, during the 1995-1996 cropping season. The objective was to determine the yield and farm profitability impact of stone terraces, which are the most common soil conservation structures used on cultivated fields in this area.

Gebremedhim et al. based the selection of the plots on (1) similar soil and geological formation; (2) slope gradient range of 20 to 30; and (3) availability of terraces at least three years of age. After selecting the watershed, seventy terraced and seventy non-terraced plots were divided equally between wheat and fava beans. In the terraced plots two quadrates of $8m^2$ were marked: one just above the terrace and another parallel but below the next upper terrace. Only one quadrate was marked on each non-conserved plots. A total of 210 quadrates were included in the study. The quadrates above the

[6] "Jornal " is the unit of measurement for a working day. In this case the authors consider 1 Jornal equals to 5 hours of work and 2 hours for lunch and rest.

terrace were designated as Soil Accumulation Zone (Accum Zone), and those under the upper terrace, Soil Loss Zone (Loss Zone); the quadrates on the non-conserved plots were designated as Control Zone (Control). Crop management was left to farmers.

Analysis of variance (ANOVA) was used to test the null hypothesis that several population means are equal. Production loss on land occupied by terraces was considered; Gebremedhim et al. adjusted yields to a per-hectare basis under the assumption of a 5% and 15% of reduction in plantable area (for a minimum of 6.67 terraces in 1 Ha and a maximum of 20 terraces in 1 Ha). The non-conserved plots were not adjusted. One-way ANOVA was conducted on both sets of yields. This allowed testing the sensitivity of yield results to assumptions regarding land loss. Also linear regression analysis was used to determine whether management differences affected the result of the ANOVA analysis. A t-test was conducted to determine whether mean fava bean yields were equal in the Accum Zone and Loss Zone, because some terraces were older than others. Finally, partial budgeting was used to evaluate profitability of investment in stone terraces. Net returns were discounted and NPV computed over 30 years. A wheat-wheat-fava bean rotation is considered to represent the dominant cropping system in the area.

The results indicate that yield of grain and straw for both crops were significantly higher in the soil accumulation zone than in the soil loss soil zone (about twice the mean yield) or in the Control plots (more than twice the mean yield). Yields from the accumulation zone were more stable than yields from the control zone. The profitability analysis shows that over a 30 year planning horizon, stone terraces yielded a 50% rate of

return. The IRR of 50% suggests the severity of the impact of soil erosion on productivity and the high potential return from investment in soil conservation in the region.

Rist et al. found that terraced fields in the Bolivian Andes increased yields between 64% and 261%, with an average of 122% for different crops (see Table 5). They conclude that the construction of terraces is a highly productive technology. These positive effects are mainly caused by the efficient use of irrigation and rainfall, efficient use of organic fertilizers and organic matter and other factors.

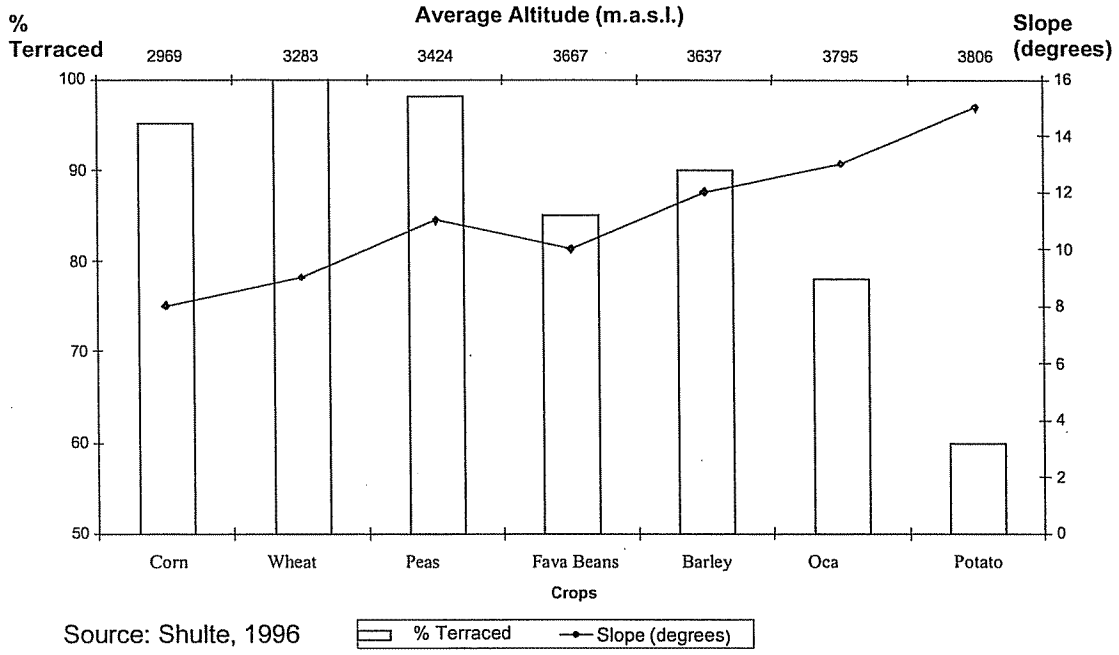
Table 5: Crop Yields in Non-Terraced vs. Terraced Fields in the Andes of Bolivia.

Zone	Crop	Control (Kg/Ha)	Terraces (Kg/Ha)	Difference %
Matarani	Radish	2600	7450	186.5
Quecoma	Onion	5300	12220	130.6
Aramasi	Potato	2256	8148	261.2
Rodeo	Onion	21400	41700	94.9
	Onion	23800	41000	72.3
	Onion	23900	39300	64.4
	Onion	20900	37000	77.0
	Onion	18900	41580	120.0
	Onion	21300	42000	97.2
Average				122.7

Source: Rist et al. (1991).

Shulte (1996) also conducted a study in the Bolivian Andes, in the Charazani Valley. He found fewer terraces as the altitude increases, but he points out that potato is preferably planted in new lands (never used before) in high mountains with high slopes where, in recent years, new terraces are being built in the zone (see Figure 5).

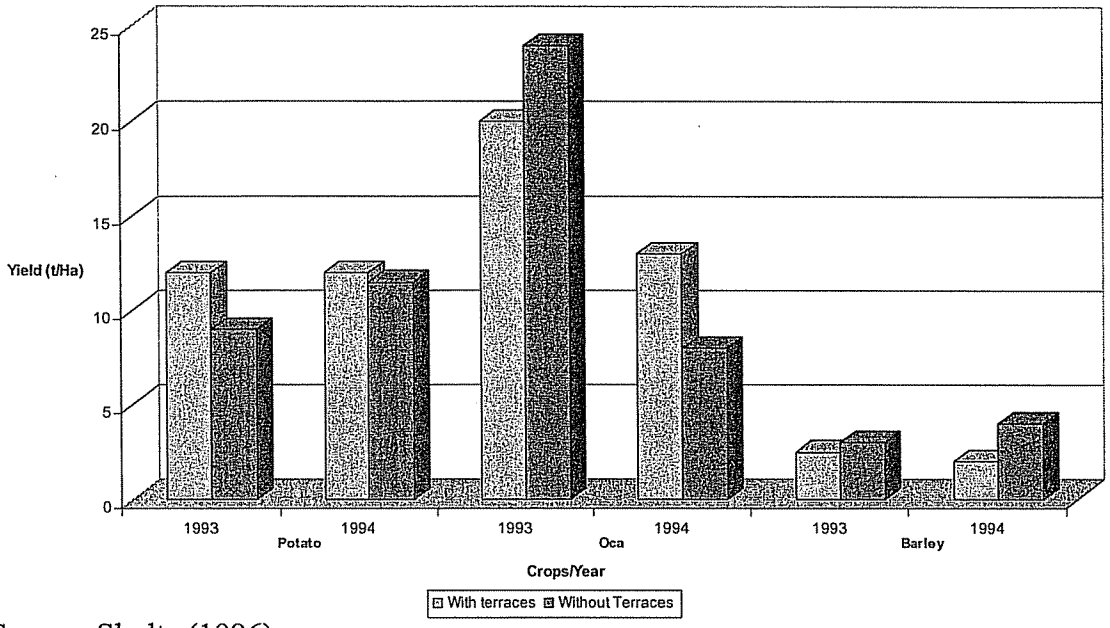
Figure 5: Terraced Fields and Slopes by Crops and Altitude. Charazani Valley, Bolivia.



Source: Shulte, 1996

Shulte found that terraces did not provide the expected positive effect on the yields of tubers (oca and potato) and barley. Figure 6 shows yields for potato, oca, and barley for the years 1993 and 1994. Although the figure shows higher yields for potato in 1993 and 1994 and for oca in 1994, Shulte believes that this may be due to the aggregation of many communities. He argues that there is just one community where the yields for these crops were high and affect the total aggregation.

Figure 6: Crop Yields in Terraced vs. Non-Terraced Fields. Charazani, Bolivia.



Source: Shulte (1996).

Garcia et al. (1990) studied some economic aspects of the terraces in Puno, Peru. In their final report they show average yields of some crops for the Andean region in Peru. In all the cases yields from crops in terraced fields are higher than yields from non-terraced fields (see Table 6). The highest percent increase in crop yields from terracing is in potato without using fertilizers where yields increased by 143%.

Garcia et al. show that for their case study that farmers used the same proportion of input quantities in both the terraced and the non-terraced fields. They used 1500Kg/Ha of potato seed, 300Kg of Ammonium Nitrate and 100Kg of Triple Super phosphate Calcium and Potassium Chloride. They also show the differences in yield response to terraced fields. As shown in Table 7, potato planted in terraced fields have about 63% higher yields per hectare than non-terraced fields.

Table 6: Crop Yields in Terraced vs. Non-Terraced Fields in the Peruvian Andes.

Crop	Yields (Kg/ha)		Increase %
	Non-Terraced	Terraced	
POTATO			
With Fertilizers	12206	17436	42.8
Without Fertilizers	4581	11131	143.0
BARLEY (GRAIN)			
With Fertilizers	1333	1940	45.5
Without Fertilizers	740	993	34.2
OAT (For pasture)			
With Fertilizers	11000	15150	37.7
Without Fertilizers	5625	7675	36.4
OCA			
Without Fertilizers	5433	9300	71.2
QUINOA			
Without Fertilizers	8500	11500	35.3

Source: Agriculture Ministry, PNCSACH, in Garcia et al. (1990).

Table 7: Potato Production and Yields in Terraced vs. Non-Terraced Fields in Puno, Peru.

Area of fields (m^2)	With Terraces		Without Terraces	
	Total Production (Kg)	Yield Kg/Ha	Total Production (Kg)	Yield Kg/Ha
528	1150.00	21780.30	--	--
320	700.00	21875.00	--	--
436	950.00	21788.99	--	--
1528	--	--	2050.00	13416.23
926	--	--	1250.00	13498.92
1262	--	--	1650.00	13074.48

Source: Garcia et al. (1990).

Treacey (1989) also compared results from terraced fields and non-terraced fields in the Colca Valley, Peru. His results also show an increase in yields for terraced fields ranging from 40% to 65% (see Table 8). Treacey suggests that terracing may be best advanced by forms of co-innovation: reintroducing the technique of terracing as an adjunct to other inputs into agricultural systems that make them more productive. Irrigation is one example, since many terraces were built expressly for irrigated

agriculture, but finding new sources of water must precede land restoration since water availability determines the rate at which abandoned terraces are restored. Treacey also points out that long term data on the yields and economic returns of terrace restoration or construction are still unavailable since most projects are very new. First year yield data from the Peruvian Ministry of Agriculture for new bench terraces (converted from non-terraced sloping fields) suggest yields rise significantly with terracing. Ministry personnel attribute the improvement to enhanced moisture retention.

Table 8: Crop Yields in Terraced vs. Non-Terraced Fields in the Colca Valley, Peru.

Crop (a)	Terraced (b)	Non-Terraced (c)	Percent Increase	N (d)
Potatoes	17206	12206	40.96	71
Maize	2982	1807	65.02	18
Barley	1910	1333	43.29	56
Barley (Forage)	23000	15865	44.97	159

(a) All crops treated with chemical fertilizer.
(b) Water absorption terraces with earthen walls and inward platform slope.
(c) Fields sloping between 20 and 50% located next to terraced fields for control
(d) N = number of terrace/field sites
Source: Treacey (1989).

In a recent study, Gonzales de Olarte et al. (1999) conducted research on terracing in Peru. They selected three different representative Departments of Peru: Cuzco, located in the south of Peru; Lima in the center and Cajamarca in the north part of the country. Comparing yields in these regions they found that the average yield of potatoes, maize and fava beans in Cuzco's terraced fields were higher than non-terraced fields. Similarly, in Lima potatoes and maize in terraces had a higher yield. In Cajamarca, maize, potatoes and other tubers (oca, olluco) and wheat had higher yields in terraced fields. They summarize the results by comparing the principal crops in Table 9.

Table 9: Average Yields (Kg/ha) of Main Crops in Terraced and Non-Terraced Fields in Three Regions of Peru.

Cajamarca	Non-terraced fields			Terraced fields						Agric. Ministry
Crop	(a)	(b)	(c)	(a)	% Incr	(b)	% Inc	(c)	% Incr	(d)
Potato	12206	2832	3800	17206	40.96	4579	61.69	4300	13.16	8571
Maize	1807	173	794	2982	65.02	1077	522.54	951	19.77	960
Barley	1333	4800	726	1910	43.29	703	-85.35	798	9.92	926
Barley (forage)	15865	n.a.	n.a.	23000	44.97	n.a.	n.a.	n.a.	n.a.	n.a.

Cuzco	Non-terraced fields	Terraced fields		Agric. Ministry
Crop	(b)	(b)	% Incr	(d)
Potato	8372	10207	21.92	8894
Maize	3038	3212	5.73	1950
Barley	3177	3002	-5.51	1309
Barley (forage)	n.a.	n.a.	n.a.	n.a.

Lima	Non-terraced fields	Terraced fields		Agric. Ministry
Crop	(b)	(b)	% Incr	(d)
Potato	4800	6812	41.9167	18860
Maize	1600	2134	33.375	1914
Barley	n.a.	1728	n.a.	1166
Barley (forage)	n.a.	n.a.	n.a.	n.a.

For Cajamarca, 1986. From Treacey (1994)

(a) Data from the Survey "Andenes y Desarrollo Rural", 1996
(b) Data from the PIDAE project (1995), La Encañada.
(c) Data from the Agriculture Ministry. Average yields, 1996. "Estadistica Agraria mensual"

Source: Adapted from Gonzales de Olarte (1999).

Because of its complex topography, La Encañada watershed basin, the area of focus of this thesis, is an interesting place for researchers in private and governmental institutions (e.g. PRONAMACHCS) dedicated to promote soil conservation practices like terracing. Although these institutions have been working for many years, little data about effects of terraces on productivity in La Encañada are available. The PIDAE Project (1995) published a book describing its work in this watershed. They also compared yields for the main crops in terraced and non-terraced fields. They found that the highest

response to the effect of slow formation terraces is on the production of peas, presumably because this crop does not require a good quality of soil. Maize, fava beans and potatoes also improved their productivity when planted in terraced fields (see Table 10).

Table 10: Crop Yields (Kg./ha) for the Main Crops in La Encañada.

Crops	Terraced fields	Non-Terraced fields	Increase %
Potato	4300	3800	13.16
Maize	951	794	19.77
Barley	798	726	9.92
Andean Tubers	6709	6331	5.97
Fava bean	755	640	17.97
Peas	830	596	39.26

Source: Ganoza (1988) in PIDAE (1995) p.60.

The authors of the PIDAE Project book also suggest that in the first years, the most important factor that increases productivity in fields with slow formation terraces is the increase of water retention. This water retention should be even more important in dry years, but there is not yet enough data to confirm this assertion.

Adoption of Conservation Practices

The literature reviewed suggests that conservation practices (in particular, slow formation terraces) increase productivity. This does not mean that slow formation terraces are necessarily profitable for farmers. Profitability depends on factors such as the interest rates, investment costs and maintenance costs. Other factors can play an important role and may not be included in simple cost-benefit analysis. Lutz et al. considers that some factors are reflected in the cost-benefit analysis to the extent that they affect prices faced by farmers. The effects of factor market distortions are reflected in

higher prices for inputs, which affect the profitability of production activities. Lutz et al. argue that institutional issues (such as land tenure and access to credit) and conservation ethics of farmers must be considered. Garcia et al. (1990), Mitchell (1985), Thampapillai and Anderson (1994), Gebremedhin and Swinton (2000), and Hagos et al. (1999), among many other researchers, have stressed that a farmer's insecure or limited tenure acts as a severe disincentive for the adoption of soil conservation practices that require substantial fixed investments. In regions where land leasing is important, (e.g. La Encañada watershed), short time contracts for land leasing and the uncertainty regarding the renewal of land leases act as deterrents to the adoption of soil conservation. Hagos et al. (1999) explains, "...tenure security determines the extent to which farmers may benefit from investments made to improve the land. In the extreme case in which farmers expect to hold land for only the current season, they will have no incentive to invest; rather, their incentive is to get the maximum that they can from the land, even if that means undermining its future productive capacity."

Another important obstacle to adoption of soil conservation practices is the lack of capital markets. When credit markets fail, farmers' inability to finance the required investments will limit adoption of conservation. Thampapillai and Anderson argue that farmers are likely to adopt profitable soil conservation practices if they have sufficient funds of their own or have access to credit. They cite other research results (Carlson et al. 1977; Earle et al. 1979; Sinden and King 1988) that indicate that farm size and farm income are positively associated with each other and, in turn, positively influence the adoption of soil conservation. This means that income and wealth determine the ability of

farmers to self-finance investments. Thampapillai and Anderson also suggest that net returns are also an important factor to adopt a conservation practice. Further, they cite the work of Veloz et al. about the economics of erosion (1985). One of the main conclusions of that work is that net returns depend importantly on the topographical characteristics of the locations. Thampapillai and Anderson explain that the heterogeneity of farm circumstances means that generalization about the private profitability of conservation practices for farmers is difficult.

Other factors that can affect the adoption of soil conservation cited in the literature include: migration and population pressure; attitudes to risk; length of planning horizon and the discount rate; production incentives and support payments; and education.

Implications of the Literature Reviewed

Some implications emerge from the literature reviewed. Literature dealing with the analysis of soil conservation practices tends to be less quantitative and more qualitative in nature. Another limitation is the frequently absent treatment of externalities associated with land degradation.

Most of the literature reviewed here compares results from experiments where crops were cultivated in terraced and non-terraced fields. There is little information about the cost of construction and maintenance of terraces. Results show in most of the cases that productivity in terraced fields is higher than non-terraced fields. However, the percentage of increasing the productivity in terraced fields is different for each experiment. The literature review shows considerable variation on the effects of terraces

on productivity. However, few studies estimate the economic returns to terrace investments. This study will provide an economic analysis of terrace investments and assess how sensitive their economic returns are to differences in terrace productivity, investment costs, and other key factors.

CHAPTER 3

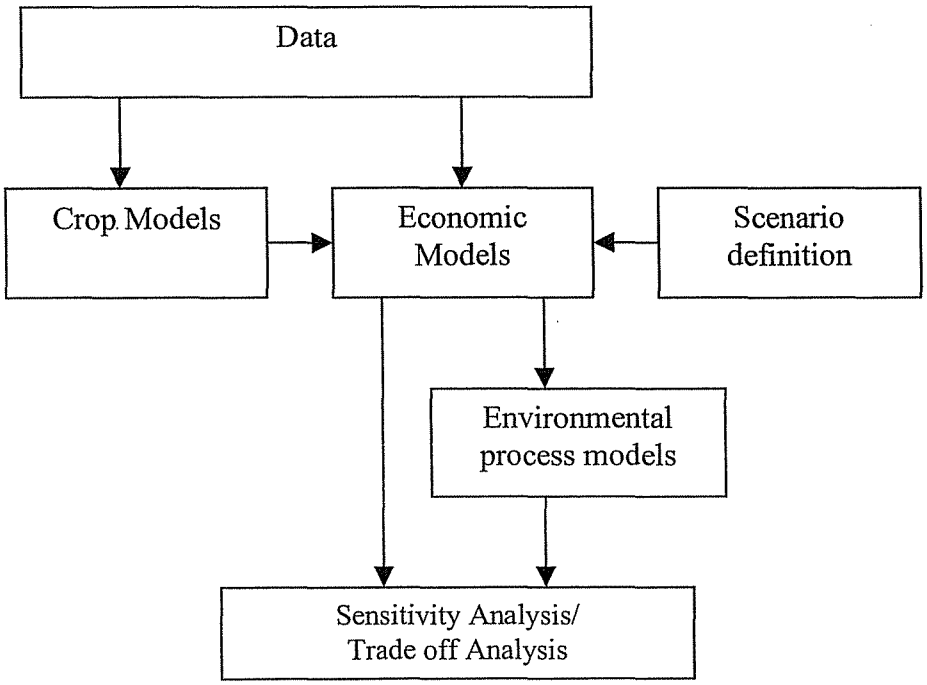
THEORY AND METHODS FOR INTEGRATED ASSESSMENT OF AGRICULTURAL PRODUCTION SYSTEMS

Introduction: The General Approach

Policy makers can analyze agricultural production systems by quantifying the relationships between agricultural production and a range of possible sustainability indicators. This process requires a multi-disciplinary approach based on bio-physical and econometric-process simulation models that can be integrated in complex software.

Stoorvogel et al. (2001) provide software to implement integrated assessment, known as the Tradeoff Analysis Model and software (see Figure 7).

Figure 7: General Approach for a Biophysical and Econometric-Process Model Integration.



Source: Stoorvogel et al. (2001).

The first level of the structure of the model is the *data* that can be experimental, environmental, or farm survey data representing the region of interest. The experimental data are needed to calibrate the models to site-specific conditions. The environmental data are inputs into the c*rop models* (bio-physical models) that estimate the spatial and temporal variation in inherent productivity caused by climate and soil variations (these data are in GIS format). These results are used as inputs into the economic models. The farm survey data are used to estimate *econometric production models*. The econometric model parameters, price distribution parameters, and inherent productivity indexes derived from the crop models are inputs into an econometric-process simulation model. The management decisions obtained from the economic simulation model are inputs to *environmental process models* to estimate impacts on soil and water resources and other environmental indicators of interest.

Different s*cenarios* are created according to each policy or technology used (e.g. crop production with and without terraces), then the simulation model is executed for a series of different variable settings (e.g. prices, discount rates, etc). Economic outcomes from the econometric-process simulation model (e.g. value of crop production) and environmental outcomes from environmental process models (e.g. soil erosion) can be aggregated to represent the different parameter values in management decisions that create *tradeoffs* between environmental and economic outcomes. The tradeoffs analysis procedure involves varying one or more model parameters while holding others fixed. Therefore, the Tradeoff Model software can be used to conduct *sensitivity analysis* to changes in parameters.

Loosely and Closely Coupled Models

The scientific community recognizes that many important phenomena involve the behavior of *complex systems* that involve the interaction of two or more subsystems (i.e. agriculture), but science currently does not have the capability to integrate disciplinary knowledge in ways that will enhance our understanding of these complex systems (Antle et al. 2001b).

Antle et al. hypothesize that "...agriculture is best understood and predicted by representing it as a complex, dynamic system with spatially varying inputs and outputs that are the result of interrelated physical and biological processes and human decision making processes..."

They define a *system* as a set of interrelated processes. There are variables that can affect the system such as the *exogenous driving variables*, which are determined outside the system but affect it by controlling or limiting the flows between the components within the system; the *endogenous variables*, which are determined within the system and include both state variables (that define the performance of the system at a specific point in time) and flow variables (inputs into and outputs from processes). A *feedback* between different processes occurs when two or more state or flow variables are linked. A *managed system* is defined as one where some of the endogenous variables are determined by purposeful human decision-making. A *managed ecosystem*[7] involves the interaction of physical, biological and human processes; therefore, agriculture is a *managed ecosystem*.

[7] Antle et al. distinguish *managed systems* from *natural systems* where the latter maybe affected by human activity that causes changes in driving variables of the system, but are not purposefully manipulated.

A managed ecosystem model can be characterized as a set of linked sub-models, each with set of drivers, state variables, flow variables and processes. Linked sub models (where state or flow variables from one sub-model are driving variables in other sub-model) are often used in current empirical research analysis on agro ecosystems. This is called a *loosely coupled modeling system*. On the other hand, when states or processes from one sub-model are linked directly to processes in another sub-model, we call this a *closely coupled modeling system*. Empirical results from both models, however, cannot tell us which one is the true model.

The Tradeoff Analysis Model software implements a loosely coupled analysis. A closely coupled model incorporates linkages between biophysical processes and management decision-making in such a way that feedbacks from one process to another can be simulated. A closely coupled model would allow us to link processes in order to more accurately reflect the interactions between biophysical and economic processes. However, at this time software does not exist to implement more closely coupled systems.

Economic Production Models

The General Approach. Economic production models are used to analyze the decision making process of farmers by using a series of econometric regression equations derived from a model of the farmers' economic behavior (Stoorvogel et al. 2001).

Economic production models are used to estimate expected returns to crop and livestock (using different scenarios that involve characteristics of land use, inputs use and the final value of production), to simulate input decisions, and estimate the value of the

production realized at the end of the growing season. Previously stated econometric production models incorporate inherent productivity into the estimation of the behavioral relationships. In this thesis, these econometric production models will be utilized within the simulation model to represent spatial variation in land use and management decisions. Crop or livestock simulation models estimate inherent productivity.

The crop growth models used are included in the DSSAT system (Decision Support System for Agrotechnology Transfer. Tsuji et al. 1994). DSSAT is a software package that includes different crop growth models (for potato, maize, rice, soybean, peanut, dry bean, chickpea, tomato, pasture, sunflower, cassava and sugarcane), database management programs, utility programs and analysis programs. DSSAT requires weather variables like rainfall, minimum and maximum temperature, and solar radiation or sunshine hours. Soil profile characteristics and cultivar-specific coefficients are also needed. Management variables are specified and the initial conditions are set for the simulation. If observed values of variables are available, they can be compared with the simulated values in order to assess the validity of the simulation. For this thesis we validated the simulation results with observed data collected in La Encañada watershed. In conclusion, econometric models incorporate the inherent productivity into the estimation of behavioral relationships that are used in the simulation model to represent the spatial variation in land use and management decisions.

Conceptual Model to Represent the Spatial Variation in Land Use and Management Decisions. Antle and Capalbo describe the production process at field *i* for crop *j* in period *t* in terms of the production function:

(1) $q_{ijt} = f(\mathbf{v}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$

where:

v is a vector of variable inputs,

z is a vector of allocable quasi-fixed factors of production and other fixed effects;

e is a vector of environmental characteristics of the field.

Then, the *expected profit function* corresponding to this production function is defined as:

$\pi_{ijt} = \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$ where p_{ijt} is the expected output price.

Define $\delta_{ijt}=1$ if the j^{th} crop is grown at field *i* at time *t* and $\delta_{ijt}= 0$ otherwise. In the event that the land is not in crop production then it is in a conserving or other productive use that earns a return π_{ict}, where *c* indicates this conserving use. Letting $\delta_{ict}= 1- \Sigma_j \delta_{ijt}$ we can define the land use decision is defined as solving:

(2) $$\max_{(\delta_{i1t}..\ \delta_{int})} \Sigma_j \delta_{ijt} \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it}) + \delta_{ict} \pi_{ict}$$

The solution takes the form of a discrete step function:

(3) $\delta^*_{ijt} = \delta_j(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{ict})$, where $\mathbf{p}_{it}$ is a vector for the p_{ijt} and likewise for the other vectors. The quantity of planned production on the i^{th} field and the variable input demands are calculated using Hotelling's lemma:

(4) $q^*_{ijt} = \delta^*_{ijt}\ \partial \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})/\ \partial\ p_{ijt} = q_{ijt}(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{ict})$

(5) $\mathbf{v}^*_{ijt} = -\delta^*_{ijt}\ \partial \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})/\ \partial w_{ijt} = v_{ijt}(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{ict})$

Antle and Capalbo (2002) state that the solution to (2) applies to a given field and is based on the assumption that each field can be managed separately. This model conveniently simplifies the linkages between economic and bio-physical processes. However some factors may cause the management of fields to be inter-related, especially where production and consumption decisions are non-separable. Also, interdependence of management decisions across fields can be caused by risk. A stochastic term can be added to the production functions assuming that these stochastic terms are jointly distributed across fields. If farmers are risk averse and choose production activities to maximize their expected utility, it can be shown that production decisions may be inter-related across fields. According to Antle and Capalbo (2002), despite this interrelationship fields can be modeled as being managed independently by risk-neutral farmers, provided that these farmers participate in input and output markets, and provided that they have access to rental markets for land and capital inputs. When these conditions do not hold, more complex models may be needed. Antle and Capalbo (2002) argued that "..a strong test of the value of risk is the ability to improve predictive power of empirical models". They tested a spatially explicit dynamic model with the assumption of risk neutrality. Their results showed that adding a risk aversion component did not increase the predictive power of the model.

Alternative Approaches: The COS, RID Model and Econometric-Process Simulation Model. An econometric model is needed to represent expected returns in the land use decision process. The classical approach would be to use a restricted profit function, but there is a practical limitation to the use of this profit function. The log-linear

or Cobb-Douglas production function is the most common functional form used in production modeling. However, when a profit function is specified in log-linear form, profit or net return is restricted to be non-negative. Actual data frequently violate this restriction since they represent realized rather than expected returns, which makes the log-linear form inapplicable.

The Cost Output Supply Model (COS). Another approach is to decompose the profit or net revenues into revenue and cost components, which are then modeled in log-linear form. The supply function derived from the restricted profit function represents the revenue component of expected returns and the cost component is represented by the restricted cost function.

Using Hotelling's lemma we can define the supply and the cost function as:

(6) $\partial \pi(p, w, z, e)/ \partial p = y(p, w, z, e)$ = Supply function

(7) $c(y, w, z, e)$ = Cost function

This system needs to be estimated jointly with the factor share equations to increase estimation efficiency. These factor share equations are estimated applying Shepard's lemma to the cost function[8].

---

[8] Mathematical Footnote: Derivation of the Factor Share Equations
Let: $\text{Ln}(c) = \beta_0 + \beta_1\text{Ln}(q) + \beta_2\text{Ln}(w_1) + \ldots + \beta_n\text{Ln}(w_{n-1})$
Where c is the variable cost function, w_i is the price of input i
To derive the Factor Share equation for input k, we derive the Cost function with respect to w_k
$\frac{\partial \ln(c)}{\partial \ln(w_k)} = \beta_{k+1}$, this expression can also be written as: $\frac{\partial c}{\partial w_k} * \frac{w_k}{c} = \beta_{k+1}$. Then, applying Shepard's Lemma, the equation can be written as $X_k * \frac{w_k}{c} = \beta_{k+1}$, rearranging and applying logarithms we obtain the factor share equation: $\ln X_k^* = \ln \beta_{k+1} + \ln(c) - \ln(w_k)$.

Then the expected net returns can be derived as:

(8) $NR = \pi(p, w, z, e) = py(p, w, z, e) - c(y(p, w, z, e), w, z, e)$

It is important to note that in this approach a single output is assumed to be grown on each field. In many cases such as agricultural production in the Andes, multiple crops are grown on a single field. The COS model which utilizes a supply function and a cost function is complicated by the existence of the jointly produced outputs. A multi-output cost function must be used, and is only well defined when the same combinations of crops are grown on all fields.

Revenue Input Demand Model (RID). This approach utilizes a revenue function and a system of factor demand functions. The revenue function is used instead of a profit function to allow for multiple crops to be grown on a single field. The same combination of crops need not be grown on every field. The Revenue function; $R = \sum_{i=1}^{n} p_i q_i$, allows some q_i's to be zero on certain fields.

This joint production model will allow us to formulate the input demand functions directly and obtain the supply functions indirectly from the revenue function. The general form of the model arises from the Envelope Theorem and is based on:

(9) $R = r(p, v, z, e)$ = Log-linear revenue function; and

(10) $v_i = v_i(p, w, z, e)$ = Factor demand functions. i=1.....n

Econometric models for potato and tubers, legumes and grains were specified in a log linear form with zero degree homogeneity of the factor demand functions in input and output prices. In the case of potato and tubers the revenue function and the factor demand functions for fertilizers, fungicides, insecticides, human labor, and animal labor were

estimated jointly using the nonlinear three stage least squares estimation method in the SAS v8. Model procedure. In the case of legumes and grains, the revenue function and the factor demand functions for human labor and animal labor were also estimated using the nonlinear three stage least squares.[9] Empirical analysis shows that the models are well behaved and that parameters estimates fall in acceptable ranges. The model was validated by comparing predicted land allocation among crops to the observed values.[10]

Then the expected net returns is derived as:

$$NR = R - \sum_{i=1}^{n} v_i w_i$$

Econometric-Process Simulation Model. The econometric-process simulation model is based on the model developed by Antle and Capalbo (2001), which is adapted here for the La Encañada case.

The simulation process begins when the model reads data used to characterize price distributions and the fields on which production will be simulated (see 'Model estimation' in Figure 8). Technical efficiency and pesticide management are defined using the production models parameters. The model reads the specific tradeoffs and scenarios parameters, which are defined by the user (e.g. terracing vs. no terracing scenarios). A simulation per field and crop cycle is then carried out. Expected returns and costs for the crops are simulated using the econometric models described above (e.g. the

[9] The use of fertilizers, fungicides and insecticides in legumes and grains are not significant in La Encañada. For this reason, only factor demand functions corresponding to human and animal labor are used in the econometric models.

[10] The parameter estimates and details of the models are available in Antle, J., Yanggen, D., and Valdivia R., "Econometric-Process Simulation Models for Analysis of Conservation Investments: Terraces in Northern Peru." Unpublished paper. Montana State University, Soil Management CRSP Project, April 2002.

RID model). The expected returns are compared, then land use with the highest return is selected and the input management decisions are simulated. Finally we will have the site-specific environmental outcomes and the site-specific economic outcomes. These outcomes are used to generate the tradeoff curves and sensitivity analysis (see Figure 8).

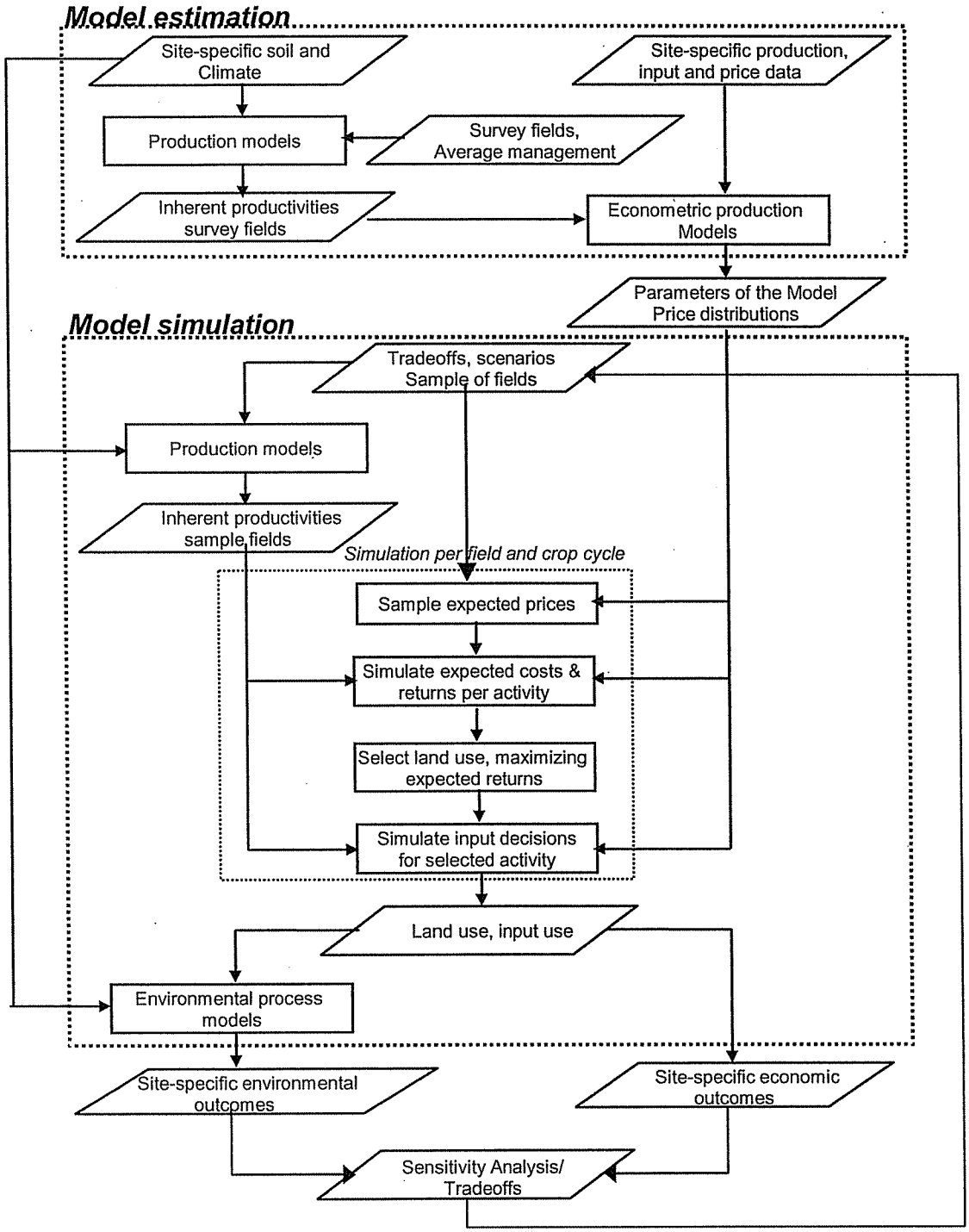
Analysis of Soil Conservation Investments:
The Case of Slow Formation Terraces

There are a number of important underlying assumptions for investment in slow formation terraces. Figure 9 illustrates how terraces may affect productivity under alternative assumptions.

Beginning with a non-terraced, undegraded field, cultivation in that field starts at time t_0 with an inherent productivity level of INP_0. If terraces are built in this field, they will increase its inherent productivity to INP_1^*. We will call this effect as an *"augmentation effect"*, and is illustrated by line II. On the other hand, if the field begins to be degraded, absent conservation practices, that field eventually will be fully degraded and the inherent productivity will reach a value of INP_0^{**} at time t_3 (line I) [11]. If terraces are built in an undegraded field at time t_1, and productivity is maintained at level INP_0, then we can say terraces have an *"avoidance effect"*. On the other hand, if terraces are built at time t_2, starting in point where land already is degraded, then terraces may have a *"restoration effect"* by returning productivity to a higher level, and may also have an *"avoidance effect"* by preventing additional losses. In this case, at time t_3 various inherent productivity levels are possible (e.g. lines III, IV and V in Figure 9).

[11] The functional form to model inherent productivity over time in degraded fields or in terraced fields is unknown. A crop simulation model (e.g. DSSAT) or a soil erosion simulation model (e.g. WEPP) could give us a better idea of the behavior of INP from t_0 to t_3.

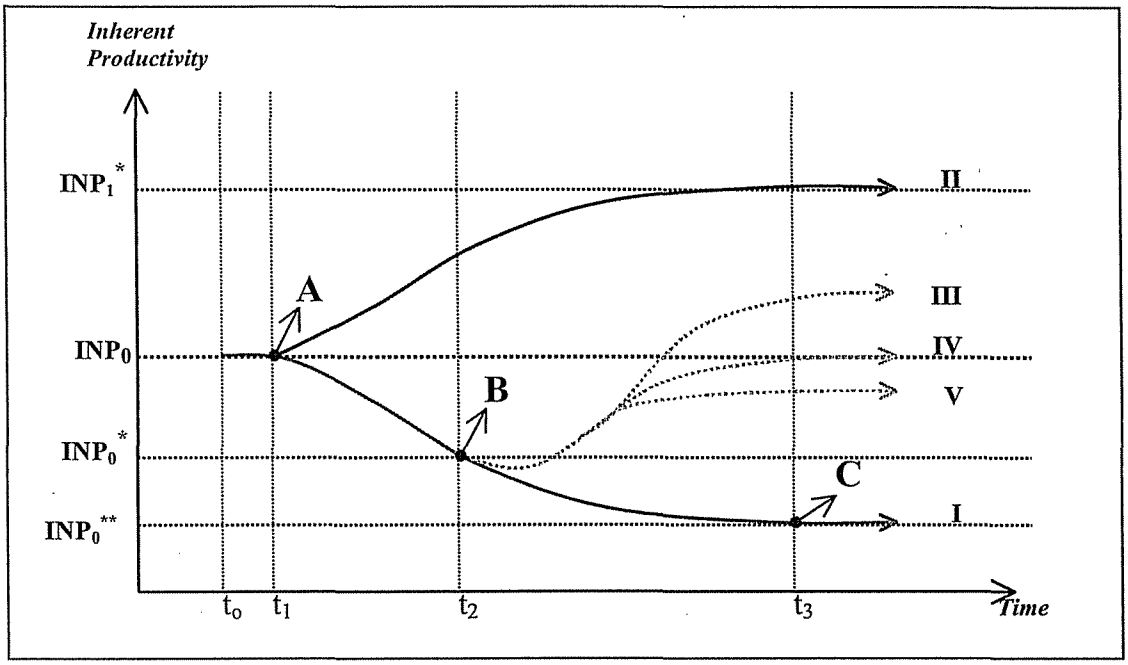
Figure 8: Structure of the Econometric-Process Simulation Model.



Adapted from Antle and Capalbo (2001).

The key point for the analysis of terrace productivity is that the state of land degradation at the time the terrace is built must be known, estimated or assumed. This state of land degradation can be measured directly, or may be proxied by variables such as years that land has been cultivated, soil depth measures, and etc. Alternatively, in a simulation analysis, the state of degradation can be specified to represent different conditions that may exist.

Figure 9: Modeling the Effects of Terraces on Productivity: The Avoidance and Restoration Effects.



Economic Analysis of Terrace Investment

Based on the assumptions explained above, the simulation model can be used to estimate the impact of terraces on inherent productivity, land use and input use. The Net

Present Value (NPV) of the production system on each land unit[12] can be used to assess the economic impacts of terraces. These impacts are estimated according to the behavior of the inherent productivity over time.

The Net Returns for the crop *i* in the period *t* are defined as:

(11) $NR_{it} = R_{it}(INP_{it}) - C_{it}(INP_{it})$

Where:

$R_{it}(INP_{it})$ = the gross return function for the crop *i* in period *t*

INP_{it} = Inherent productivity of the crop *i* in period *t*

$C_{it}(INP_{it})$ = Variable costs = $\Sigma_j w_{ijt} v_{ijt}(INP_{it})$

w_{ijt} = Price of the input j for the crop *i* in period *t*

v_{ijt} = Quantity of the input j used for the crop *i* in period *t*

The terraces investment model based on the estimation of the NPV is defined as:

$$(12)\ NPV = \sum_{t=1}^{T} D_t(NR_t - MC_t) - FC_0$$

Where:

T = number of crop cycles (each crop cycle have 6 months)

$D_t = (1/(1+r/2))^t$ = Discount rate and *r* is the annual interest rate.

$NR_t = \max(NR_{it})$ = maximum expected net returns for each crop period

MC_t = Terrace Maintenance cost for each period

FC_o = Fixed investment costs for terraces on each land unit

A number of variables that can affect the NPV such as the discount rate, investment and maintenance costs, prices, and etc. can be identified. Changes in these

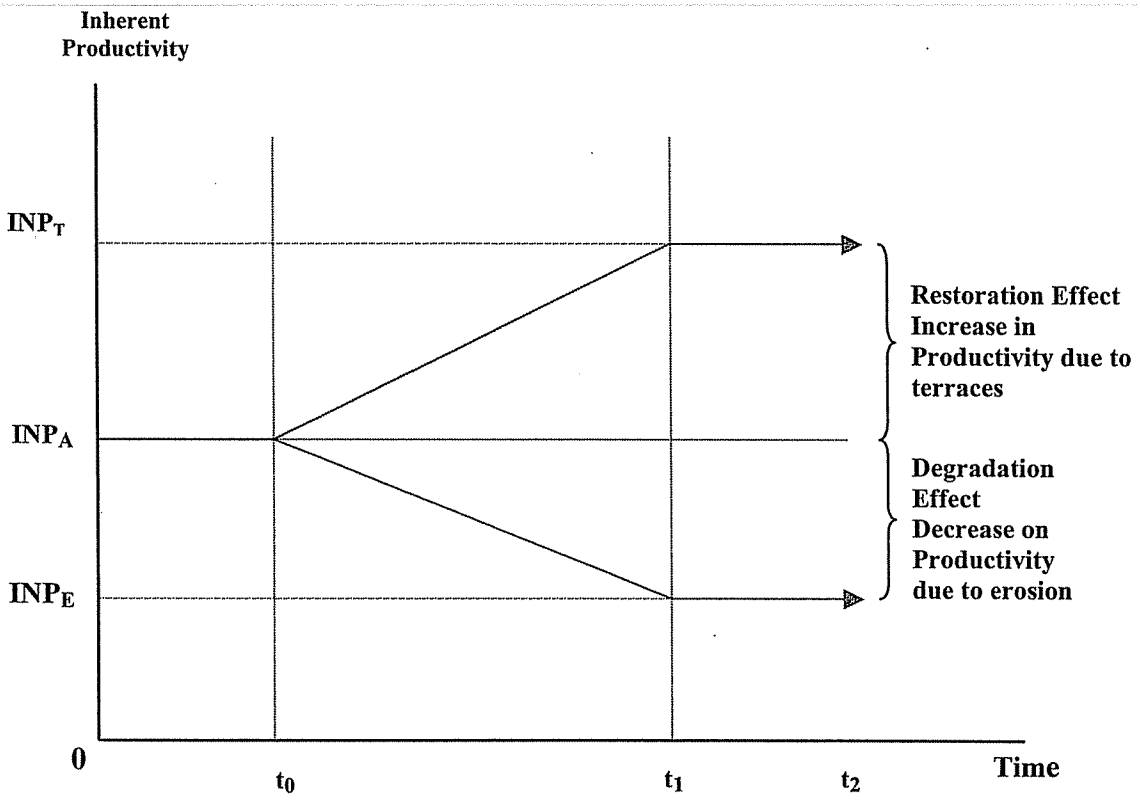
[12] We defined a "sub-parcel" as the land unit for this study.

variables can be used to conduct sensitivity analysis to determine how they affect the results of the model. Two scenarios are considered to assess the impacts of terraces on inherent productivity (see Figure 10):

1. **Erosion effects on fields without terraces**. Productivity decreases from the initial value of the inherent productivity INP_A in period t_0 to the final value INP_E in period t_1 due to erosion. The value for the percentage effect of this decrease is $(INP_E/INP_A)x100$ <100. When the economic simulation is executed the productivity will be decreased by (INP_E/INP_A) x $100/(t_1 - t_0)$ percent each period.
2. **Restoration effect on fields with terraces**. Productivity increases from the initial value of the inherent productivity INP_A in period t_0 to the final value INP_T in period t_1 after terraces are established. The value for the percentage increase in productivity is (INP_T/INP_A) x100 >100. When the economic simulation is executed the productivity will be increased by (INP_T/INP_A) x $100/(t_1 - t_0)$ percent each period.

Inherent productivity is defined as a function of input use and other management decisions $\underline{m}^o$, but also depends on other biophysical variables such as slope and soil quality. They are represented by the vector $\underline{c}$. Then, the Inherent productivity is defined as: $INP = f(\underline{m}^o, \underline{c})$. In this study we use the assumption that INP is a function of slope to simulate the field-specific effects of terraces on productivity.

Figure 10: Effects of Erosion and Slow Formation Terraces on Inherent Productivity.



As stated before, it is assumed that a field's inherent productivity changes over time as a function of degradation caused by erosion and as a function of terracing. Productivity changes are assumed to follow a linear path from the beginning of the simulation through a specified number of crop cycles (TTIME) to an upper-bound value (Figure 10).

All fields have the same upper-bound values for the productivity effects of terraces and erosion (BATPROD and BAEPROD respectively). A value for the upper-bound productivity effect of terraces is specified as $100 \leq$ ATPROD $\leq$ BATPROD where ATPROD is the actual increase in productivity due to terraces. A value for the upper-

bound productivity effect of erosion is also specified as BAEPROD≤AEPROD≤100 where AEPROD is the actual decrease in productivity due to erosion.[13]

The values for the productivity effects of terraces and erosion are a function of each field's slope:

(13) ATPROD=(100 + (BATPROD-100)*(PSLOPE/100)**ATCURV)

(14) AEPROD=(100 - (100-BAEPROD)*(PSLOPE/100)**AECURV)

Where:

BATPROD = the upper bound value of ATPROD attained when field slope (PSLOPE) approaches 100%.

BAEPROD = the lower bound value of AEPROD attained when field slope (PSLOPE) approaches 100%.

ATCURV = curvature parameter for ATPROD function.

AECURV=curvature parameter for AEPROD function.

Figure 11 illustrates the effect of slope on inherent productivity, when the base inherent productivity is INP_o[14]. The effects of terraces and erosion on inherent productivity are estimated as:

(15) $INP_{TI}= INP_o * (1 + (ATPROD-1)/TTIME)$

(16) $INP_{EI}=INP_o * (1 + (AEPROD-1)/TTIME)$

Where, INP_{TI} is the increased inherent productivity due to terraces, and INP_{EI} is the decreased inherent productivity due to erosion.

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[13] The base value of BATPROD=100 simulates the case of no terracing and the base value of BAEPROD=100 simulates the case of no productivity effect of erosion.

[14] The base Inherent productivity INPo is estimated using a crop simulation model and validated using observed data.

Dashed lines in Figure 11 are different functional forms representing these productivity effects. Soil scientists have suggested that this is a non-linear relationship.[15] Figure 11 shows for example, a field with no terraces and with 50% slope[16] the inherent productivity will be INP_{E1}. On the other hand, the same field with terraces will have an Inherent productivity of INP_{T1}. Then, the total effect of the terraces on productivity is measured by the difference $INP_{T1} - INP_{E1}$..

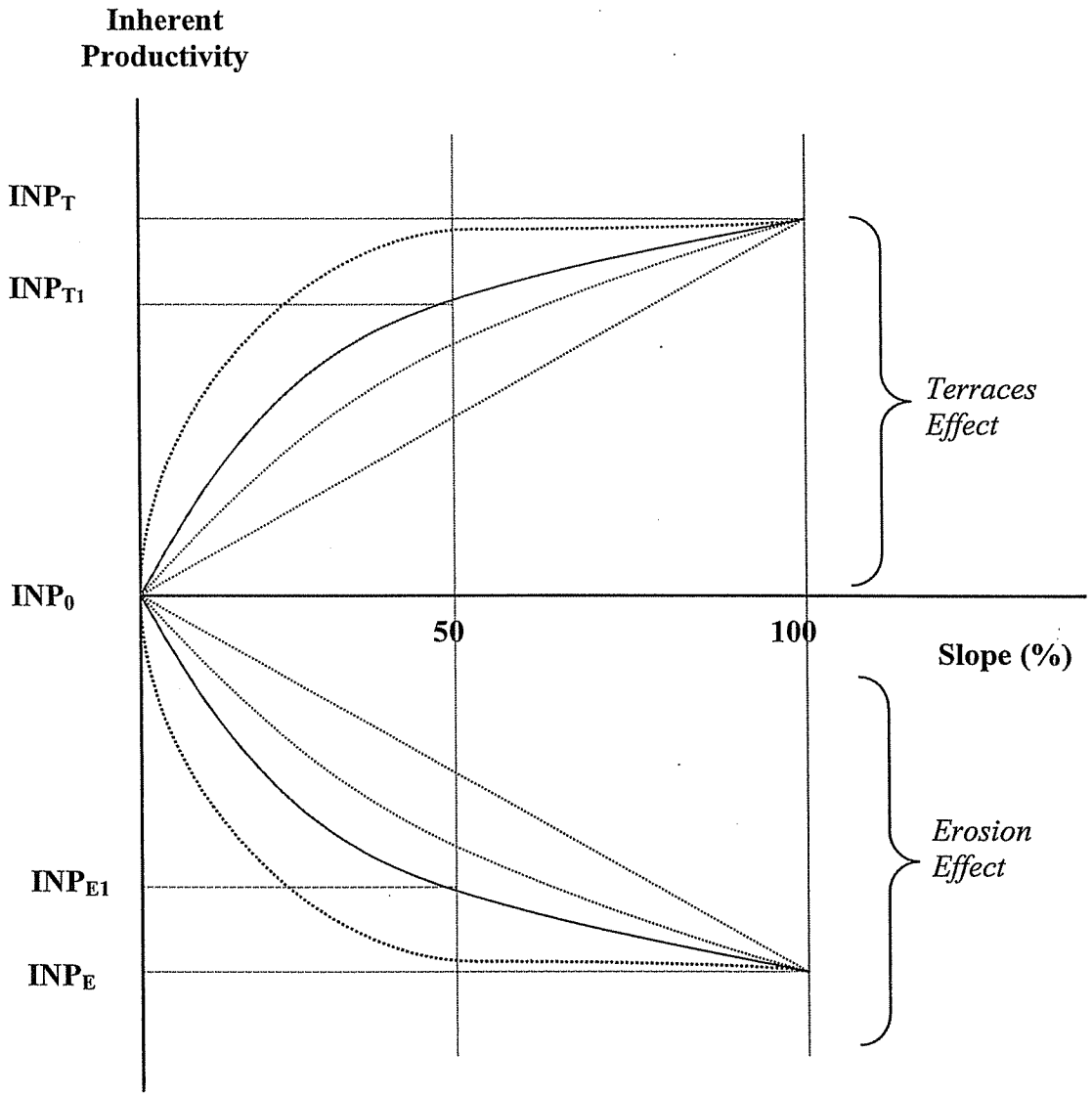
Sensitivity Analysis of Soil Conservation Investments
Using Integrated Assessment Models.

The General Approach. Uncertainty in a model can have different origins in different decision problems. It may be due to either incomplete information, or fluctuations inherent in the problem, or unpredictable changes in the future. A model can be affected by changes in either parameters or drivers (exogenous variables).

For example, consider a model of the form $Y = f(\underline{x}, \alpha)$, where $\alpha \sim N(\mu_\alpha, \sigma^2_\alpha)$, and $\underline{x}$ is a vector of exogenous variables. To determine the effects of the uncertainties from a parameter α with a known probability distribution, one can use Monte Carlo statistical methods. But these methods are often difficult to apply to the vector of exogenous variables $\underline{x}$ because their joint distribution is not known.

[15] There is no available data about the functional form to represent the effects of erosion and terraces on productivity. Soil scientists working in related topics have suggested a non-linear form. For this thesis, the parameters ATCURV and AECURV have been set at 0.3 to provide a curve with an intermediate slope..
[16] Slope: 100% = 45 degrees

Figure 11: Impacts of Slope on Inherent Productivity for Scenarios With and Without Terraces.



One may tackle uncertainties in a more "deterministic" manner. The approach is called various names such as "scenario modeling", "deterministic modeling", "sensitivity analysis", and "stability analysis". The idea is to subjectively come up with a ranked list of higher-level uncertainties that might presumably have a bigger impact on the eventual

result. This is done before focusing on the details of any particular "scenario" or model. An understanding of the influence of the above on the course of action suggested by the model is crucial because different levels of acceptance (by the general public, by the decision-makers, by stakeholders) may be attached to different types of uncertainty (Arshan, 1994).

Different parameters impact differently on the reliability, robustness, and efficiency of the model. The relevance of the model (its appropriateness to the task) strongly depends on the impact of the parameters to the outcome of the analysis. There are various reasons why sensitivity analysis could be used. The most important could be:

- Testing the robustness of an optimal solution. Robustness of implications to changes in key parameters will tell us the relevance of the parameters and the model.
- Identifying critical values, thresholds, or break-even values where the optimal strategy changes.
- Identifying sensitivity to important variables.

Integrated analysis is an interdisciplinary process that combines, interprets and communicates knowledge from diverse scientific disciplines in an effort to investigate and understand causal relationships within and between complicated systems. Methodological approaches employed in such assessments include computer-aided modeling, scenario analyses, simulation and participatory integrated assessment that are based on existing experience and expertise (IPCC report, 2001).

The IPCC report (2001) provides some indication of sensitivity to alternative climate models by comparing results from several different models or model variants. These comparisons show that model results are highly sensitive to alternative climate model inputs, reflecting the wide range of yield impacts that have been estimated with crop models. The limited sensitivity analysis performed suggests that uncertainties in economic models alone are large and further imply that the economic impacts of climate change on agriculture are given low degree of confidence. The implication is that econometric and integrated assessment modelers need to undertake sensitivity analysis to determine key assumptions and parameters and focus quantitative analysis on those dimensions of the models. Current approaches to conduct sensitivity analysis include the Monte Carlo Approach and the Scenario Analysis.

The Monte Carlo Approach. Monte Carlo methods arise from experimental mathematics, a method of experimenting using random numbers. Problems handled by Monte Carlo methods are either probabilistic or deterministic depending on their treatment of the random processes. For probabilistic problems the simplest Monte Carlo approach is to observe random numbers, chosen in such a way that they directly simulate the physical random processes of the original problem, and to infer the desired solution from the behavior of these random numbers (Hammersley and Handscomb, 1964).

This observational Monte Carlo approach assumes that the selected parameters are defined by their statistical distribution. This is probably the most frequent method to deal with uncertainties and to conduct sensitivity analysis. However, this approach is limited by some factors when complex models are used. Scientists have expressed

concern that scientific investigation requires a long sequence of observational records, replicable trials, or model runs, like the Monte Carlo simulations, so the results can be specified in formal statistical characterization of the frequency distribution of outcomes being assessed. Most complex system models cannot possibly be put to every conceivable test to find the frequency of occurrence of some socially or environmentally salient event. The popular philosophical view of "objective science" as a series of "falsifications" breaks down when it confronts systems that cannot be fully tested (IPCC report, 2001). One of the key factors in these models is functional form, which cannot be easily studied using Monte Carlo analysis.

Several factors contribute uncertainty to modeling bio-physical impacts on agricultural systems. Biophysical parameters are calibrated (or measured) in labs; they are not statistically estimated. For instance, in the case of integrated assessment of agricultural production models the uncertainty increases when bio-physical models are linked to econometric models to predict changes in land use, crop choice, production, prices and impacts on economic welfare of producers and consumers.

Another important source of uncertainty in crop models is the spatial resolution of crop models. For example, the IPCC report 2001, states that crop models simulate processes that regulate growth and development at fine scales (a few kilometers), whereas climate change scenarios that drive crop models typically are produced by climate models operating at coarse scales (1000 Km or more). Studies that use statistical downscaling techniques have shown large simulated yield discrepancies between coarse-resolution and fine-resolution. Spatial analog models use reduced-form econometric

models that are based on historical data and estimate the relationship between economic variables and biophysical variables. Another limitation to this approach, and perhaps the most important, is that many of the key variables have unknown distributions. Variables such as individual discount rates or parameters from biophysical models do not have known distributions because as it was mentioned before, they are not statistically estimated.

Therefore, these models cannot be used to simulate the effects of bio-physical changes on economic outcomes, a simple Monte Carlo approach cannot capture effectively the effects of bio-physical changes (e.g. occurrence of frost, pests, etc) on economic outcomes. For these reasons, the use of Monte Carlo approach is more than complicated in this type of models since this approach was created basically for analysis of statistical models.

Scenario Analysis or Parametric Approach. The alternative approach to the Monte Carlo methods is the use of ranges since distributions of some parameters are unknown.

In this approach one assumes scenarios by specifying ranges and combinations (e.g. certain combinations of possible values of selected parameters). By solving the problem repeatedly for different scenarios and studying the solutions obtained, the researcher observes sensitivities and heuristically decides on an approximation, which is subjective. The process of identification of the key parameters, the specification of ranges or the assignment of specific values (i.e. maximum, minimum values) and the combinations to evaluate the model are also in most of the cases a subjective decision.

A scenario is a description of a plausible future without estimation of its likelihood. Scenarios may contain several sources of uncertainty but generally do not acknowledge them explicitly. Projected ranges can be constructed from two or more scenarios in which one or more sources of uncertainty may be acknowledged.

The integrated simulation model composed of the linked econometric and biophysical components allows comparisons of tradeoffs among economic and environmental outcomes by varying some of the important parameters (i.e. output prices, interest rates, and etc.) and creating different scenarios to be compared. Therefore, we can use the Trade-off Analysis as a device to conduct a sensitivity analysis with the information produced by an integrated, multidisciplinary analysis or integrated assessment models.

Trade-off curves can be used as a method for summarizing the tradeoffs among the objectives of interest. In economic terms, the tradeoff curves provide essential information for making choices among policy and technology alternatives, because they show how much of one desired outcome, such as agricultural production, must be given up to obtain a unit of some other desired outcome (Crissman, et al. 1998).

CHAPTER 4

CASE STUDY: SENSITIVITY ANALYSIS OF TERRACE INVESTMENTS IN LA ENCAÑADA, CAJAMARCA, PERU

Introduction

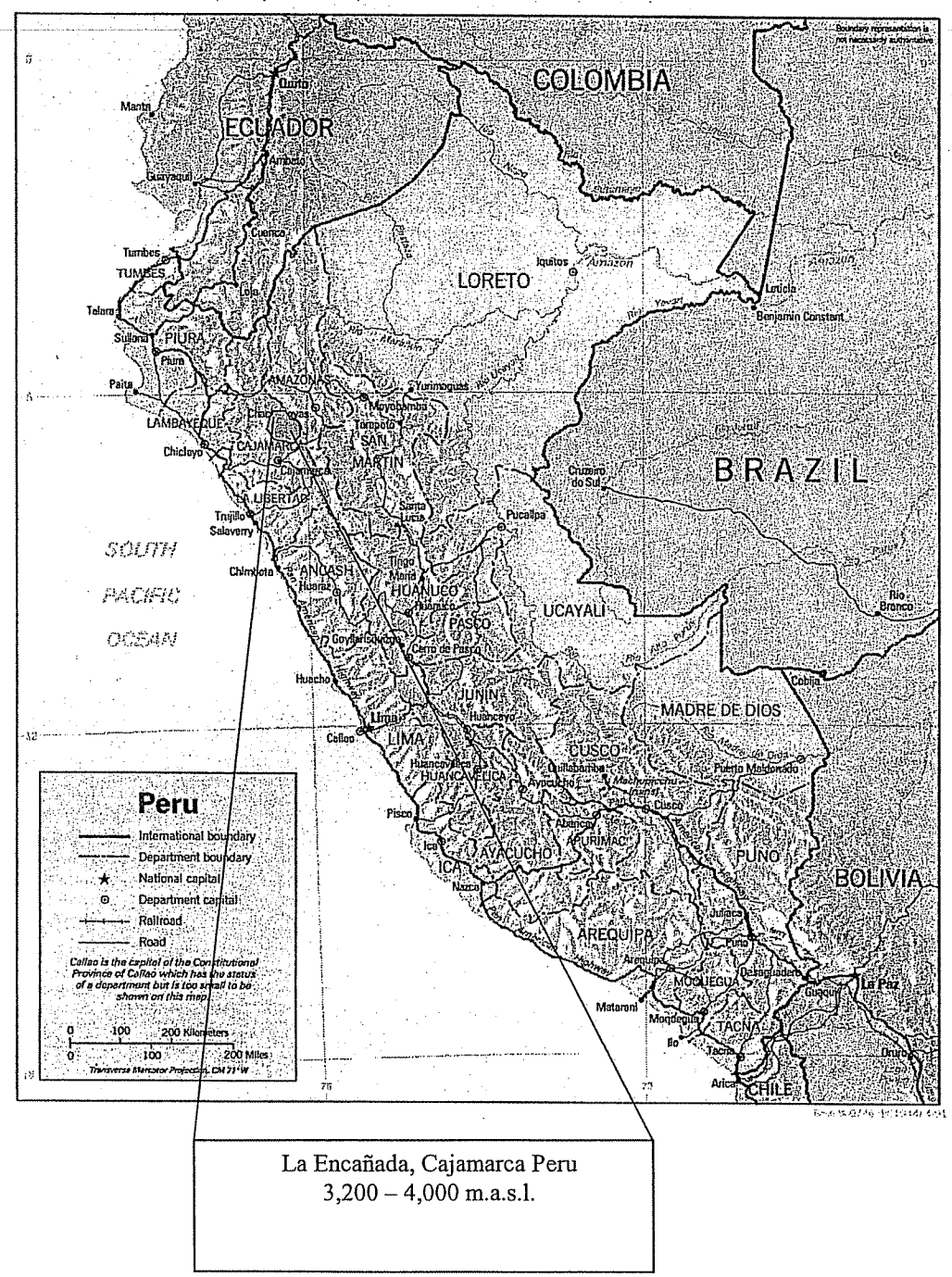
In this chapter, results from a sensitivity analysis of terrace investment are presented. The La Encañada watershed is first briefly described, and the data are explained. The design of the sensitivity analysis is described, and a list of selected variables used under different scenarios is defined. Results of the sensitivity analysis of terrace NPV for all the scenarios are presented. The final section uses the sensitivity analysis results in an economic analysis of terrace investments.

Location

The study will be carried out with data from the watershed basin of La Encañada, Department of Cajamarca in the northern Andes of Peru (see Figure 12). La Encañada is located between the parallels 7°00'00'' and 7°20'00" South latitude and between the meridians 78°30'00' and 78°50'00'' West Longitude. The altitude of the watershed varies from 3,200 to 4,000 m.a.s.l.[17]

[17] Meters above sea level

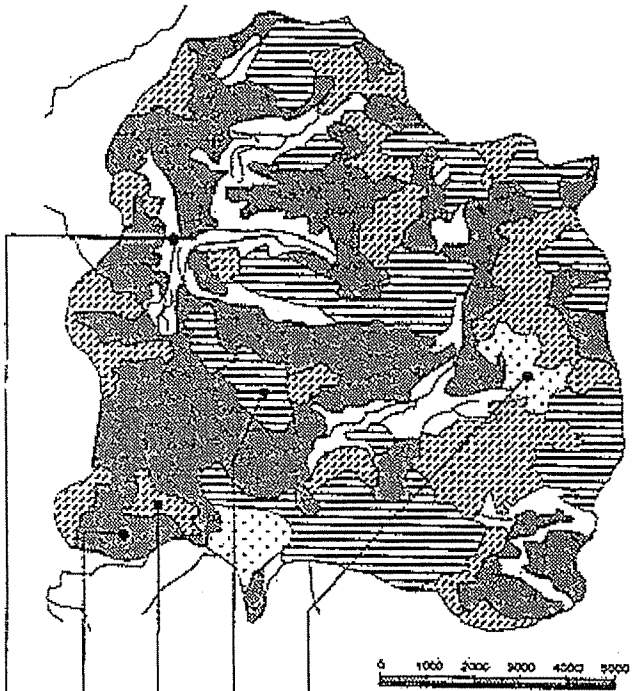
Figure 12: La Encañada, Cajamarca, Peru.



According to the PIDAE Project (1995) only 10% of the land in the La Encañada basin has little slope (mostly in the valley bottoms). About two thirds of the land is

hillsides with heterogeneous topography (more than 50% of land in the basin has slopes greater than 15%) and high rates of erosion. One fourth of the land is located in the 'jalca'[18] (upper hills) where frost occurrences are the most important limitation for cropping (See Figure 13).

Figure 13: Land Extension According to the Slope.



Type	Slope (%)	Area (Ha)	Percent
A	0-8	400	3.40
B	8-15	2,294	19.40
C	15-25	2,386	20.20
D	25-50	5,118	43.30
E	>50	1,617	13.70
Total		11,815	100.00

Source: PIDAE, 1995

[18] 'Jalca", local name of an agro-ecological zone (above 3,400 masl) which is characterized by having pastures and mostly dedicated to livestock production.

The La Encañada watershed has three main ecological zones: valley, hillside (or lower hills) and jalca (upper hills). Each of these zones reflects specific environmental and production conditions that vary with altitude (Bernet 1999). These characteristics are specified in Table 11.

Table 11: La Encañada, Characteristics According to the Ecological Zone.

Criteria	**Valley**	**Hillsides/Lower hills**	**Jalca (Upper Hills)**
Altitude (m.a.s.l.)	2500-3200	3200-3500	>3500
Frost Occurrence	High	Medium	High
Average Temperatures	High	Medium	Low
Access to Irrigation	Almost 100%	Almost none	Partial
General Soil Quality	Good	Bad	Good
Main Crops	Permanent Pastures	Potatoes, cereals	Fodder crops, potatoes
Number of Livestock	High	Low	Medium
Purpose of Livestock	Milk Production	Animal Traction	Milk and Traction
Number of Sheep	Low	High	Medium

Source: Bernet, 1999

According to Bernet (1999), the economic situation of farmers in La Encañada watershed is strongly determined by the differences in climate, topography, and access to irrigation in relation to the three ecological zones, creating a different set of production activities with their constraints for each zone.

Farm size in La Encañada is small, less than 3 hectares on average, therefore incomes are also very low and farmers have difficulties saving money for investments. Production for home consumption is important to secure the family's nutrition. However, selling the surplus of agricultural production is equally important to acquire products that cannot be produced by farmers themselves. These are products like rice, sugar, intermediate production inputs (fertilizers, pesticides, etc.), and other commodities as

well as public services (e.g. transport). The relative importance of livestock and crop production varies among the three ecological zones. Milk production dominates in the Valley because access to irrigation allows for cultivation of permanent pastures, primarily ryegrass-clover mixtures. In the hillsides and lower hills zones without irrigation, field crops dominate the production system, with cultivation occurring in two seasons, December to May and June to September/November. In the upper hills a combination of agricultural and livestock production exists. This zone is favorable for natural pastures.

The production system of La Encañada includes crops such as potato, Andean tubers, legumes, cereals and pastures. La Encañada has about 1,800 ha of cropland. It also produces about 3,000 and 4,000 liters of milk daily. Production of wood and logs also contributes to the economy of farmers in this zone.

The Sample

The data was collected by the research project "Tradeoffs in Sustainable Agriculture and the Environment in the Andes: A Decision Support System for Policy Makers"[19] from 1997 to February 2000. The sample is 36 farmers chosen randomly along the watershed. Each farmer manages from 5 to 10 fields. The average of hectares in the sample is about 78ha per crop cycle and about 21ha (27 percent) are terraced fields (Valdivia, 1999). The data were divided into 8 groups:

- Parcel level Information. Includes general information about ownership, area, number of terraces, altitude, location (measured by a GPS) and other variables.

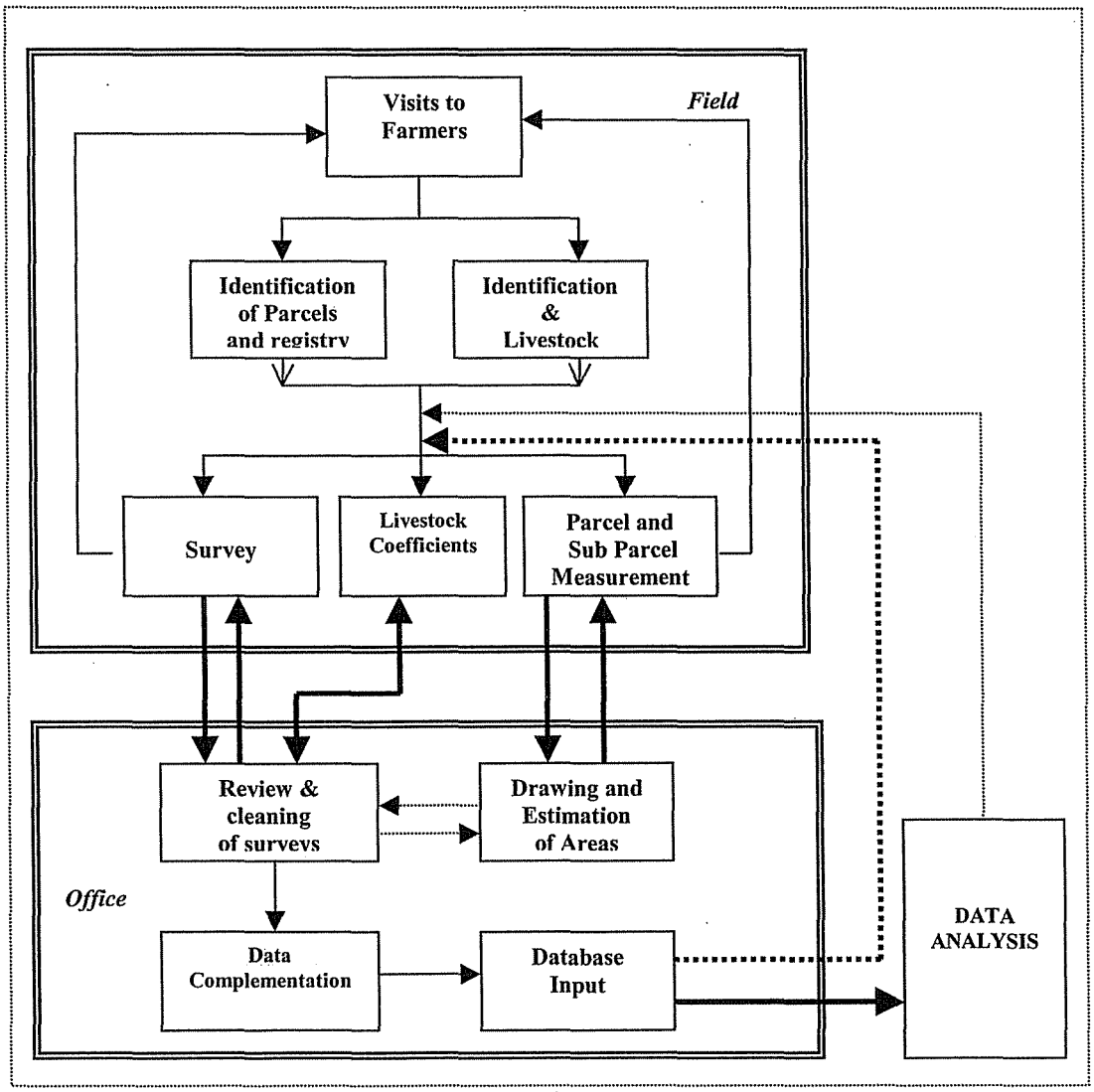
[19] Project funded by the SM-CRSP/USAID, in collaboration with Montana State University and the International Potato Center, Peru.

- Sub-parcel Level Information. Includes information about the slope, access to water, crop cultivated and previous crop rotation.
- Sub-parcel Labor Information. Includes information about labor use by activity per day. Also includes labor cost information.
- Sub-parcel Equipment and Services. Includes information about the use of equipment and services (quantities and costs).
- Sub-parcel Supplies Information. Includes information about the use of supplies like seeds, fertilizers, fungicides and others (quantities and costs).
- Sub-parcel Potato and Tubers. Since the most important crop in this area is potato (and some Andean tubers), information was collected about the quality of the production and its use (e.g. market, self consumption, seed, etc.), and prices.
- Sub-parcel Harvest Information. Includes information about crop yields, quality and final use (e.g. market, self-consumption, seed, etc), prices.
- Sub-parcel Land Ownership and Crop Financing. Includes information about land access, availability of credit, and sources of funding and interest rates.

The process of collecting data started with the preparation of surveys to collect agricultural and livestock data. Frequent visits to farmers allowed collection of data about farmer's activities as carried out in a cropping season. Answers to the surveys were double-checked many times in order to decrease the risk of getting erroneous information. Data from surveys were complemented with additional information (e.g. the market price of fertilizer) and also with drawings of the parcels and sub parcels and their

respective areas. Once checked, the information was entered into the databases where it was again checked for errors. Additional information about terraces was collected during February to July, 2000. Data about the size of terraces, slope, labor costs and other variables were included in this database. The data collection and recording process is described in Figure 14.

Figure 14: Process of Collecting Data in La Encañada, Cajamarca, Peru.



Source: Adapted from Valdivia (1999).

Software

The Microsoft Access software was used to input the data and manage the databases. SAS V.8 was used for cleaning and analyzing the data. Finally, the Trade-off Analysis Model software was used to conduct the sensitivity analysis and to estimate final results.

Design of Sensitivity Analysis

As explained in Chapter Three, variables such as individual discount rates or parameters from biophysical models do not have known distributions because they are not statistically estimated. Therefore, the scenario analysis approach is used to conduct sensitivity analysis. In this approach different scenarios are constructed by specifying ranges and combinations of key parameters. Since the model has many parameters, it is not feasible to use all the possible combinations of them. Instead, we first consider individual parameters and selected combinations of parameters. Thus, to conduct a sensitivity analysis we must identify the most important parameters that affect productivity.

Identifying the Key Parameters. The objective of the sensitivity analysis is to determine how sensitive the model is to changes in one or more parameters that are used in policy analysis. Therefore, we focus on a set of parameters that show both an effect on productivity and an effect on different policies (e.g. subsidies).

Recall equations (12), (13), (14), (15) and (16) from Chapter 3:

$$(12)\ NPV = \sum_{t=1}^{T} D_t(NR_t - MC_t) - FC_0$$

where:

T = number of crop cycles (each crop cycle has 6 months)

$D_t = (1/(1+r/2))^t$ = Discount rate and *r* is the annual interest rate.

$NR_t = \max(NR_{it})$ = maximum expected net returns for each crop period

MC_t = Terrace Maintenance cost for each period

FC_o = Fixed investment costs for terraces on each land unit

(13) ATPROD=(100 + (BATPROD-100)*(PSLOPE/100)**ATCURV)

(14) AEPROD=(100 - (100-BAEPROD)*(PSLOPE/100)**AECURV)

where:

BATPROD = the upper bound value of ATPROD attained when field slope (PSLOPE) approaches 100%.

BAEPROD = the lower bound value of AEPROD attained when field slope (PSLOPE) approaches 100%.

ATCURV = curvature parameter for ATPROD function.

AECURV=curvature parameter for AEPROD function.

(15) $INP_{TI} = INP_o * (1 + (ATPROD-1)/TTIME)$

(16) $INP_{EI} = INP_o * (1 + (AEPROD-1)/TTIME)$

where INP_{TI} is the increased inherent productivity due to terraces and INP_{EI} is the decreased inherent productivity due to erosion.

From these equations, the key parameters that affect the NPV were chosen to conduct the sensitivity analysis. These parameters are:

- **BAEPROD**. This parameter is the lower bound value of AEPROD attained when field slope (PSLOPE) approaches 100% and represents the negative effects of erosion on inherent productivity. The base value is 100, and the minimum feasible value is zero (see equations (13) to (16) and Figure 11).
- **BATPROD**. This parameter is the upper bound value of ATPROD attained when field slope (PSLOPE) approaches 100% and represents the positive effects of terraces on inherent productivity (see equations (13) to (16) and Figure 11). The base value is 100. Based on data from the region and the literature reviewed in Chapter two, the range of values of BATPROD was set from 25% to 225%.
- **Interest rate.** Farmers in the population are believed to possess different, unobserved time-rates of discount due to their different financial circumstances. To account for this situation, the interest rate used is randomly generated from a triangular distribution (a minimum, maximum and a mode value are specified to generate the interest rate variable). An accepted approach for modeling a source of randomness in the absence of data is to use a triangular distribution. It is often used in risk analysis and in analysis where subjective probabilities need to be estimated (Anderson et al. 1977, Pantanali 1996, Valdivia et al. 1996, Norton and Alwang 1998). Values were selected to represent plausible ranges relative to

market interest rates. For this study, the minimum, mode and maximum base values of interest rate were set at 20%, 25% and 30% respectively.

- **TERINV**. This parameter represents the fixed investment cost of establishing a terrace in the first cropping cycle (see equation (12)). Values were derived from survey data and from estimates from the literature.
- **TERMAN**. This parameter represents the terrace maintenance costs. This is a variable cost. We assume that farmers do maintenance of terraces every cycle of production, so this costs is the same during all the cropping cycles (see equation (12)).
- **TTIME.** This parameter represents the number of crop cycles required for a slow-formation terrace to "mature". We assume that inherent productivity of a field will increase up to the point where terraces are fully mature. From this point, inherent productivity is constant over time (see equations (5) and (16), and Figures 9 and 10 in Chapter Three). Based on expert opinion, terraces are assumed to mature in 5-20 crop cycles.

Construction of Scenarios. Using the variables explained above, different scenarios were constructed to conduct the sensitivity analysis. Table 12 shows the detailed structure of all the scenarios used in the sensitivity analysis. These scenarios are:

Table 12: Structure of the Scenarios .

		Scenario	TRADEOFFS AND SCENARIOS DEFINITION									
Scenario	Figure #	Code	BAEPROD	BATPROD	TERINV	TERMAN	ncycles	ttime	IR Min	IR Mode	IR Max	Description
BASE	Figure 15	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
1	Figure 16	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AE1E	100-0	100	100	100	20	10	100	100	100	No Terraces, irate=100, Erosion Effect
2	Figure 17	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AT1T	100	125-325	100	100	20	10	100	100	100	Terraces Effect
3a	Figure 18	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AIT1	100	125	100-0	100	20	10	100	100	100	Subsidy Investment, Battop=125
		AMT1	100	125	100	100-0	20	10	100	100	100	Subsidy Maintenance , Battop=125
		AIM1	100	125	100-0	100-0	20	10	100	100	100	Subsidy Inv & Main, Battop=125
3b	Figure 19	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AIT2	100	200	100-0	100	20	10	100	100	100	Subsidy Investment, Battop=200
		AMT2	100	200	100	100-0	20	10	100	100	100	Subsidy Maintenance , Battop=200
		AIM2	100	200	100-0	100-0	20	10	100	100	100	Subsidy Inv & Main, Battop=200
4	Figure 20	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AIR1	100	125	100	100	20	10	25-175	40-160	45-155	Interest Rates, Battop=125
		AIR2	100	200	100	100	20	10	25-175	40-160	45-155	Interest Rates, Battop=200
5a	Figure 21	ABB1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AT05	100	125-325	100	100	20	5	100	100	100	Terraces Effect, Ttime=5
		AT10	100	125-325	100	100	20	10	100	100	100	Terraces Effect, Ttime=10
		AT15	100	125-325	100	100	20	15	100	100	100	Terraces Effect, Ttime=15
		AT20	100	125-325	100	100	20	20	100	100	100	Terraces Effect, Ttime=20
5b	Figure 22	ABB1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AIR1	100	125	100	100	20	10	25-175	40-160	45-155	Interest Rates, Battop=125
		AIR2	100	200	100	100	20	10	25-175	40-160	45-155	Interest Rates, Battop=200
		AIR5	100	125	100	100	20	5	25-175	40-160	45-155	Interest Rates, Battop=125, ttime=5
		AIR6	100	200	100	100	20	5	25-175	40-160	45-155	Interest Rates, Battop=200, ttime=5
5c	Figure 23	ABA1	100	100	100	100	20	10	100	100	100	No Terraces, No Erosion. Base case
		AIT5	100	200	100-0	100	20	5	100	100	100	Subsidy Inves. Battop=200, ttime=5
		AMT5	100	200	100	100-0	20	5	100	100	100	Subsidy Maint, Battop=200,ttime=5
		AIM5	100	200	100-0	100-0	20	5	100	100	100	Subsidy In& Man, Battop=200, ttime=5

BAEPROD : Lower Bound for Erosion Effects on Productivity
BATPROD : Upper Bound for Terraces Effects on Productivity
TERINV : Terrace Investment Cost Changes (%). Base value 100=US$300.00
TERMAN : Terrace Maintenance Cost (%). Base value 100=US$65.00
ncycles : Period of analysis (Cropping Cycles)
ttime : Time to achieve full maturity of terraces (Cropping Cycles)
IR Min : Minimum Values for Interest rate (%). Base value 100=20%
IR Mode : Modal Values for Interest Rate (%). Base value 100=25%
IR Max : Maximum Values for Interest Rate (%). Base value 100=30%

- ***Base Case*:** This analysis represents the cases where parcels have no erosion effects and no terraces. This case will be used to evaluate the other scenarios.
- **Scenario 1: *Erosion:*** This scenario is used to assess the effects on the NPV of the production system. The parameter used is BAEPROD.
- **Scenario 2: *Terracing:*** This scenario compares the base case (no terraces) against fields with terraces. The parameter used BATPROD is the upper bound for effects of terracing on productivity.
- **Scenario 3: *Subsidies:*** This scenario compares the base case (no terraces) against different levels of subsidy on terrace investment, terrace maintenance, and both investment and maintenance of terraces together. The parameters used are TERINV and TERMAN. Simulations are made for various levels of BATPROD.
- **Scenario 4: *Interest Rate:*** This scenario compares the base case (no terraces) against the effects of changing the interest rate parameters (IRMIN, IRMODE, IRMAX) at various levels of BATPROD.
- **Scenario 5: *Time of terrace maturity*:** This scenario compares the base case (no terraces) to terraced fields with different times of maturity (TTIME). Scenarios 2 to 4 will be tested for different values of TTIME.

Sensitivity Analysis Results

Sensitivity analysis was conducted using a sample of 100 fields simulated over 20 cropping cycles. To determine what sample size was needed to represent the variability in

the watershed, samples of 50, 100 and 150 fields were tested. Results showed that there was a significant difference between parameters estimates with a sample of 50 fields and a sample of 100 fields. On the other hand, there was no significant difference between parameters estimates with a sample of 100 fields and a sample of 150 fields. Therefore, a sample of 100 fields was found to be adequate. The simulation model is able to replicate each simulated observation. For this analysis, 3 replications were used. The Net Present Value is measured in US dollars per hectare. The results for each scenario are as follows.

Base Case. Undegraded Fields Without Terraces

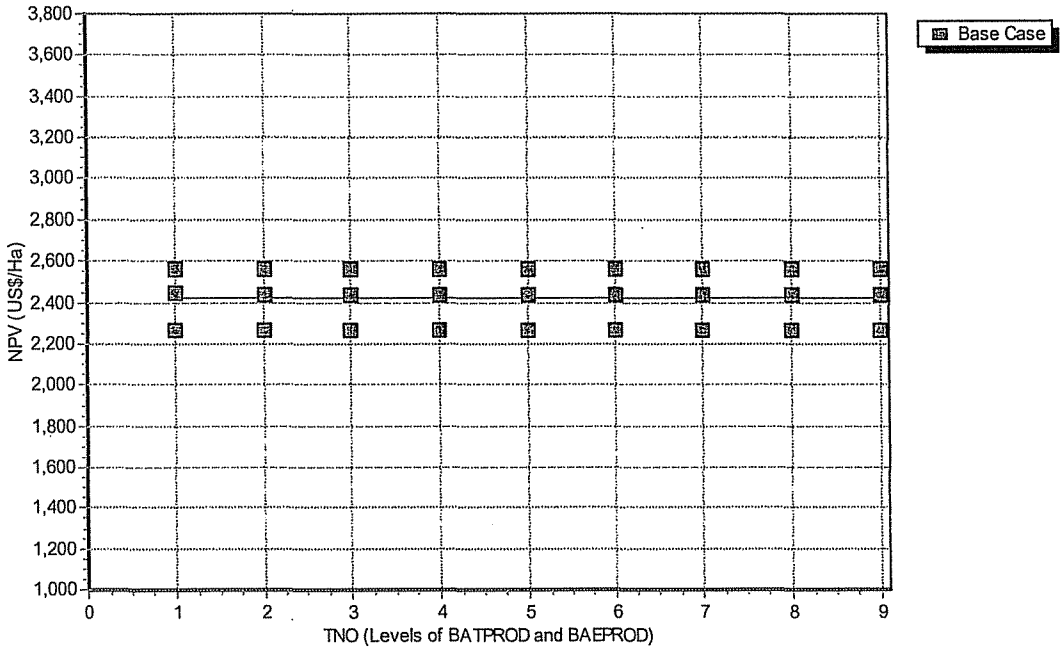
In the base case, NPV (US$/Ha) of undegraded fields without terraces has been estimated. Figure 15 shows these results. The trade-off points (TNO) represent the different values of BAEPROD and BATPROD used in the sensitivity analysis. In this case, they are set to be 100 (No terracing or Erosion effect). Each of the three points in the graph represents the average of NPV for 100 fields for a replication. To facilitate interpretation of the results, a line fitted through these points is presented in the graphs.

The result for the base case shows that fields with no erosion and no terraces have Net Present Value of about $2,425 per hectare on average. According to the PIDAE project (1995), in La Encañada, the value of a hillside land with "moderate level of erosion, without soil conservation, and for agricultural use"[20] ranges from US$1000 to US$1400 per hectare. Price for non-degraded lands are around US$2400. (PIDAE, 1995). In this sense, the values obtained in the sensitivity analysis appear to give a good

[20] This study does not define what this means in a way that it can be related to the productivity of the land. Therefore we cannot compare it directly to our analysis.

approximation of land value. The base case will be included in the following scenarios to facilitate their interpretation.

Figure 15: Base Case: Undegraded Fields Without Terraces.

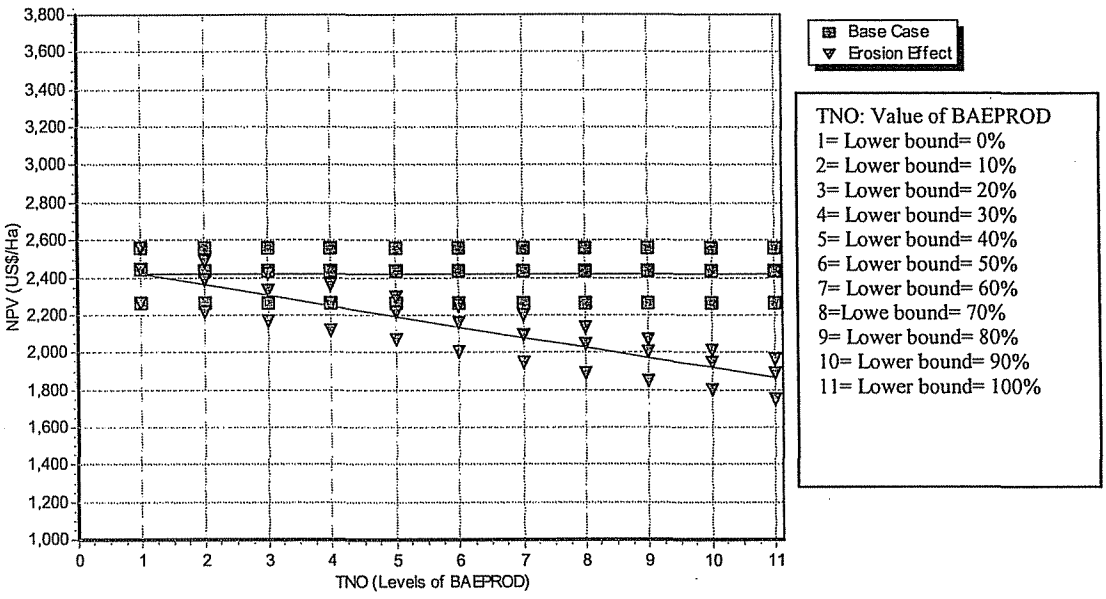


Scenario 1. Erosion

Figure 16 shows the effects of different levels of erosion on NPV per hectare. The results of this scenario show that returns to the production system decline as the productivity effects of erosion increase. The first tradeoff point (TNO=1) represents fields with no erosion, so the corresponding NPV value is the same as in the Base Case. The eleventh tradeoff point (TNO=11) represents the case where the effect of erosion on productivity approaches 100% on steeply- sloped fields (BAEPROD=100). From Figure 15 we can infer that undegraded fields have an estimated NPV of $2,425 per hectare, in average. On the other hand, heavily degraded fields have an average estimated NPV of

$1,850 per hectare. A moderately degraded field, (e.g. with BAEPROD=60 at the point TNO=5 in Figure 16) earns an average NPV of $2,200 per hectare.

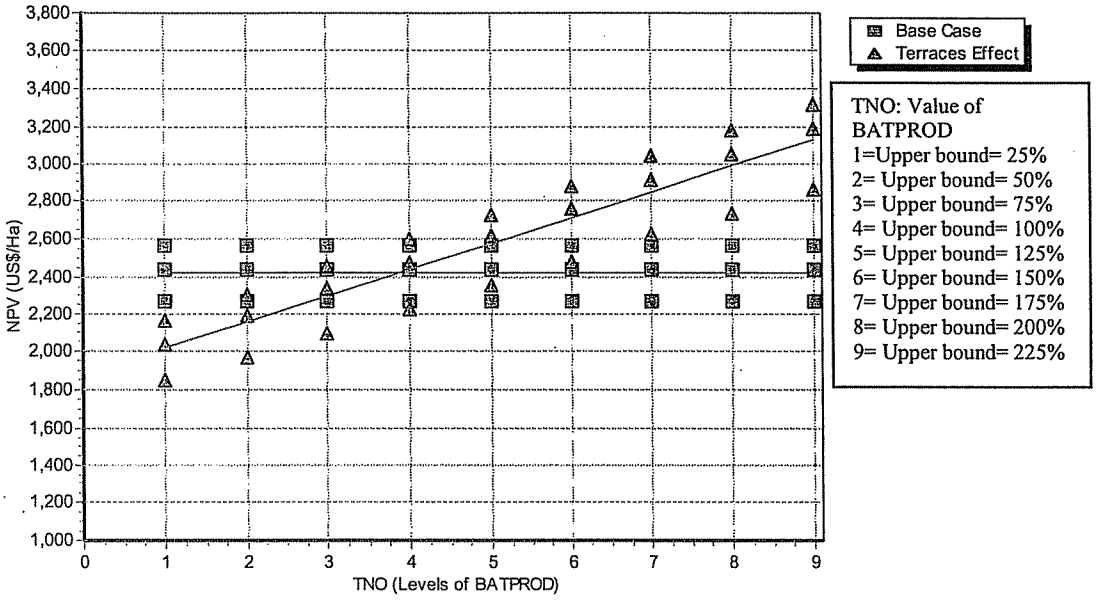
Figure 16: Scenario 1: Average of NPV (US$/Ha) for Different Levels of Erosion.



Scenario 2. Terracing

In this scenario, the tradeoffs points represent different values of BATPROD (the upper bound on the productivity increase with terraces). Figure 17 shows that the first tradeoff point, TNO=1, that represents fields with an increase on inherent productivity of up to 25% (BATPROD=125) have an average NPV of $2000 per hectare. The fourth tradeoff point (TNO=4) represents a value of BATPROD of 200, in other words, a maximum effect on inherent productivity of 100%. At this point, the average NPV is about $2430/Ha, almost the same NPV as the Base case. Higher values of BATPROD give NPVs that exceed the value on the base case.

Figure 17: Scenario 2: Terracing Effect.

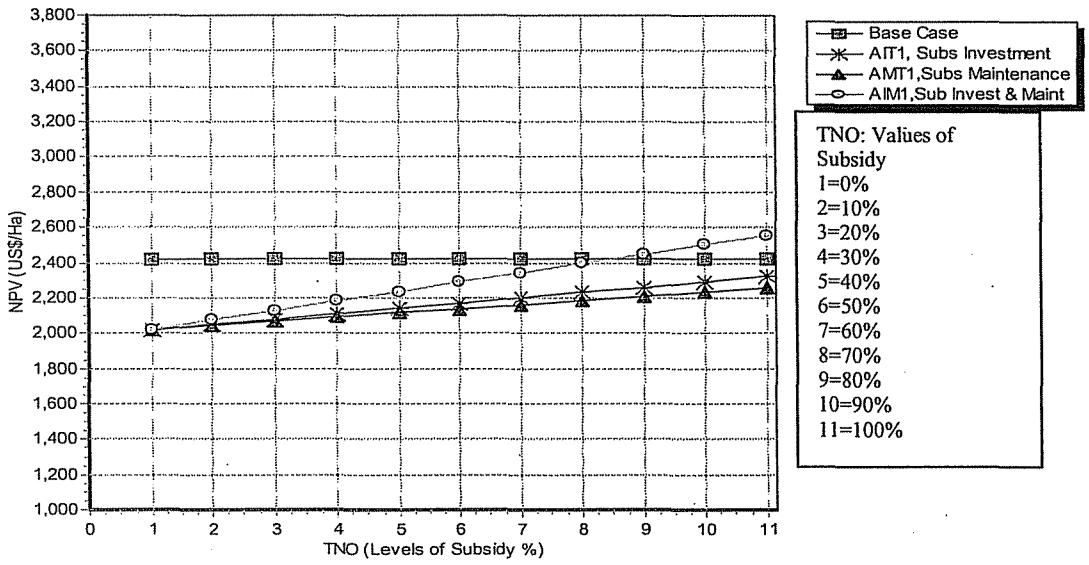


Scenario 3. Subsidies

Results show that returns to investment on terraces are sensitive to the parameters TERINV and TERMAN that represent the terrace investment and terrace maintenance costs respectively. Figure 18 shows the effects of different levels of subsidies for fields with a low effect of terraces on inherent productivity (upper bound value of BATPROD=25% of increase). The first tradeoff point (TNO=1) represents the case when there are no subsidies (farmers bear the full cost of maintenance and investment of terraces). The average NPV is about $2000. This scenario also compares the effects of subsidizing only investment costs, subsidizing only maintenance costs, and subsidizing both investment and maintenance costs.

Figure 18 shows that terraces with low levels of productivity (BATPROD=125) are profitable relative to the base case only with an 80% or higher subsidy of terrace investment and maintenance cost.

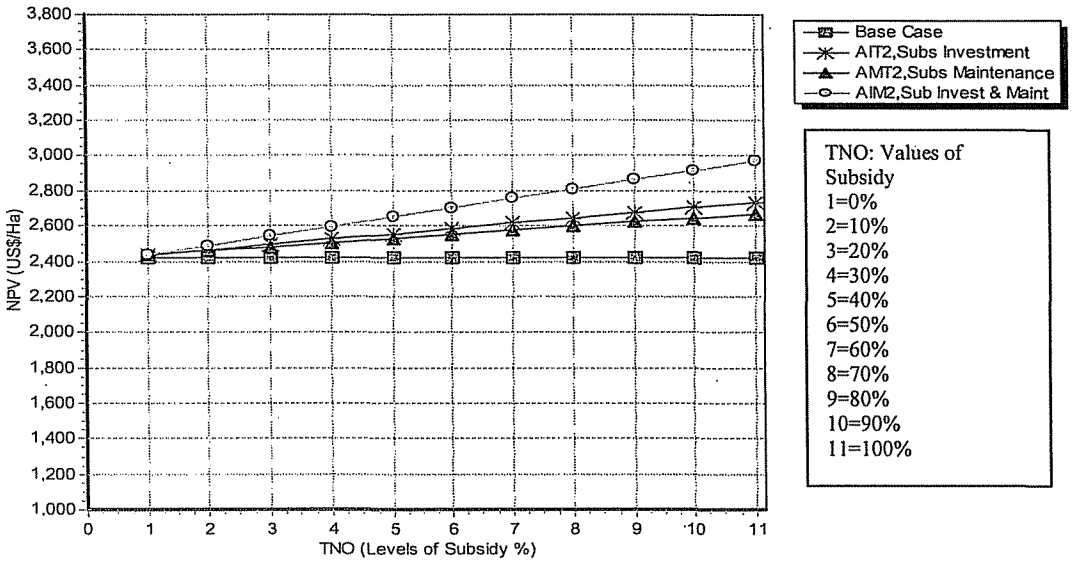
Figure 18: Scenario 3a: Low Level of Productivity Effect and Subsidies.



AIT1 : Subsidy in investment costs for low productivity fields
AMT1 : Subsidy in maintenance costs for low productivity fields
AIM1 : Subsidy in maintenance and investment costs for low productivity fields

On the other hand, when terraces have a greater effect on productivity (a higher upper bound value of BATPROD) the results show that subsidies may not be necessary to make terraces profitable. Figure 19 shows the case when BATPROD=200 (an upper bound of 100% of increase of inherent productivity). The first tradeoff point (TNO=1, the zero subsidy case) shows that terraces earn an average NPV comparable to the base case without terraces (See Figure 17). Therefore, any amount of subsidy gives an average NPV with terraces that is greater than the base case.

Figure 19: Scenario 3b: High Level of Productivity Effect and Subsidies.

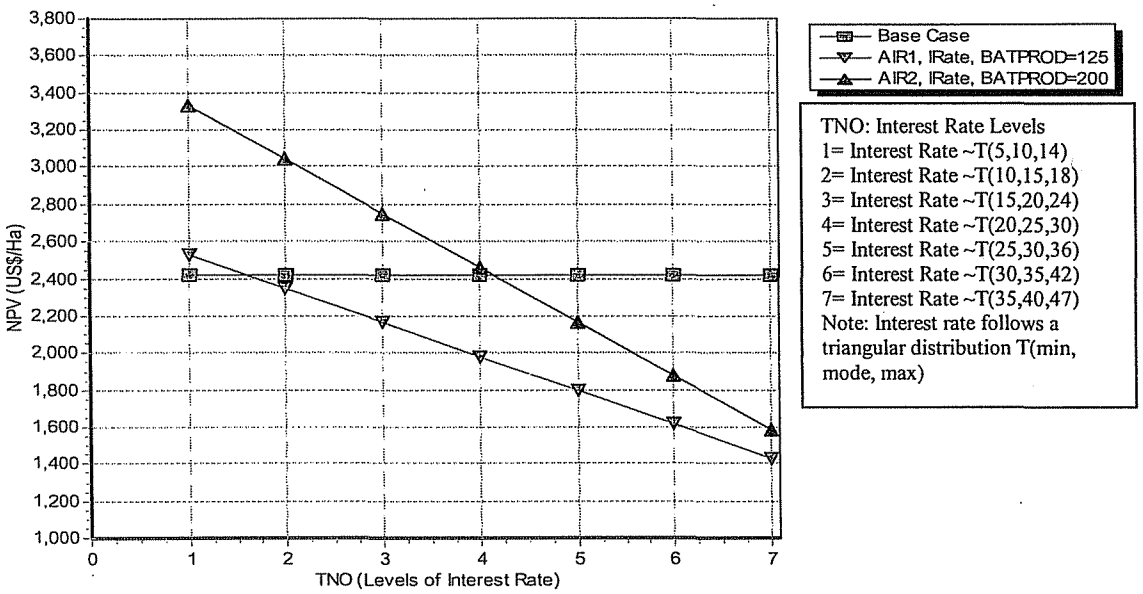


AIT2 : Subsidy in investment costs for high productivity fields
AMT2 : Subsidy in maintenance costs for high productivity fields
AIM2 : Subsidy in maintenance and investment costs for high productivity fields

Scenario 4. Interest Rate

Figure 20 shows the results for two different levels of BATPROD as the parameters of interest rate distribution are changed (the interest rate follows a triangular distribution T(min, mode, max)). For the low productivity case (BATPROD=125) we can see that with very low interest rates, terraces can be profitable relative to the Base Case giving an average NPV of about $2500/ha. At higher interest rates the average NPV can fall to $1400/ha. Figure 20 also shows that for higher levels of productivity (BATPROD=200), returns to investment are more sensitive to the interest rate. With a low interest rate, these fields earn an average NPV of $3300/ha, but with higher interest rates the average NPV falls to $1600 per hectare.

Figure 20: Scenario 4: Changes in Interest Rate for Different Levels of Productivity.

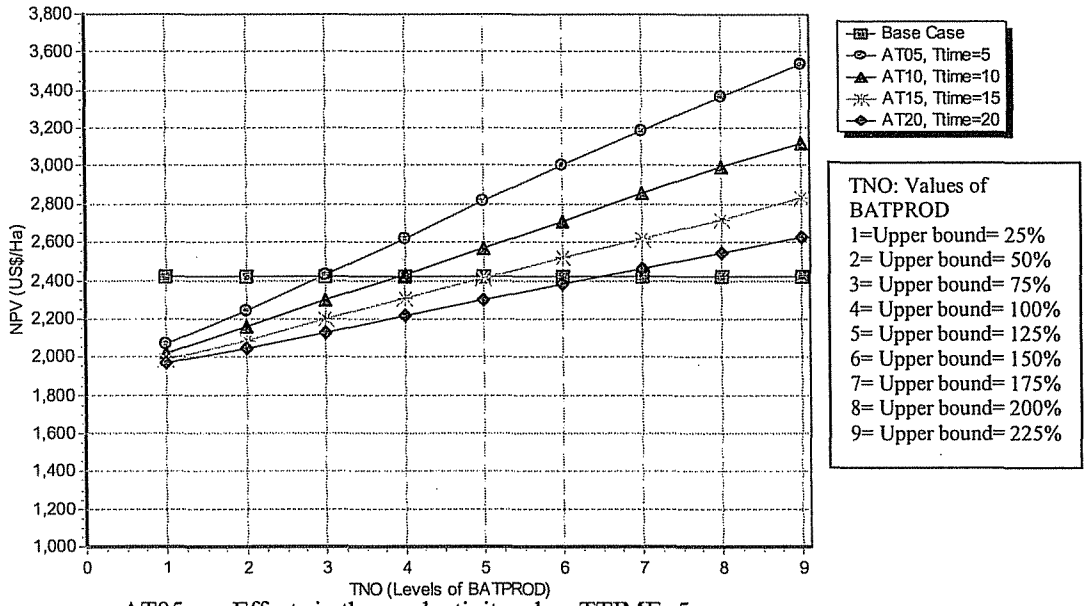


AIR1 : Changes in interest rate for low productivity fields (BATPROD=25%)
AIR2 : Changes in interest rate for low productivity fields (BATPROD=100%)

Scenario 5a: Time of Maturity of Terraces and BATPROD.

Different values for TTIME (time required to achieve full maturity of terraces) are compared in Figure 21. Results show that there is an inverse relationship between TTIME and NPV. The slope of the relationship between BATPROD and NPV increases as TTIME decreases, showing that there is an interaction between terrace productivity and time to maturity.

Figure 21: Scenario 5a: Effects of the Time of Maturity of Terraces.



AT05 : Effects in the productivity when TTIME=5
AT10 : Effects in the productivity when TTIME=10
AT15 : Effects in the productivity when TTIME=15
AT20 : Effects in the productivity when TTIME=20

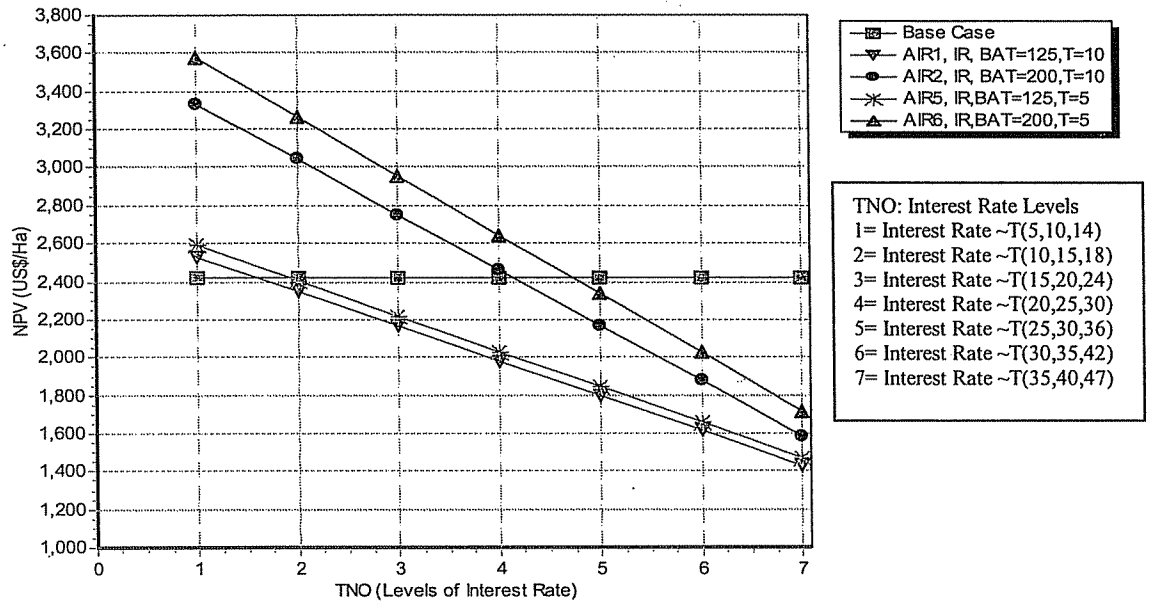
Scenario 5b: Time of Maturity of Terraces and Interest Rate.

Figure 20 showed that returns to investment are sensitive to changes in interest rate for different levels of productivity effects. Figure 22 illustrates the same case when TTIME is changed. Figure 22 shows that there is not a strong interaction between TTIME and interest rate effects in the simulation model.

Scenario 5c: Time of Maturity of Terraces and Subsidies.

This scenario is the combination of Scenario 3 (Subsidies) with changes in the value of TTIME. Figure 18 illustrates different levels of subsidies for fields with low level of productivity (BATPROD=125). In that case, the TTIME value was set at 10.

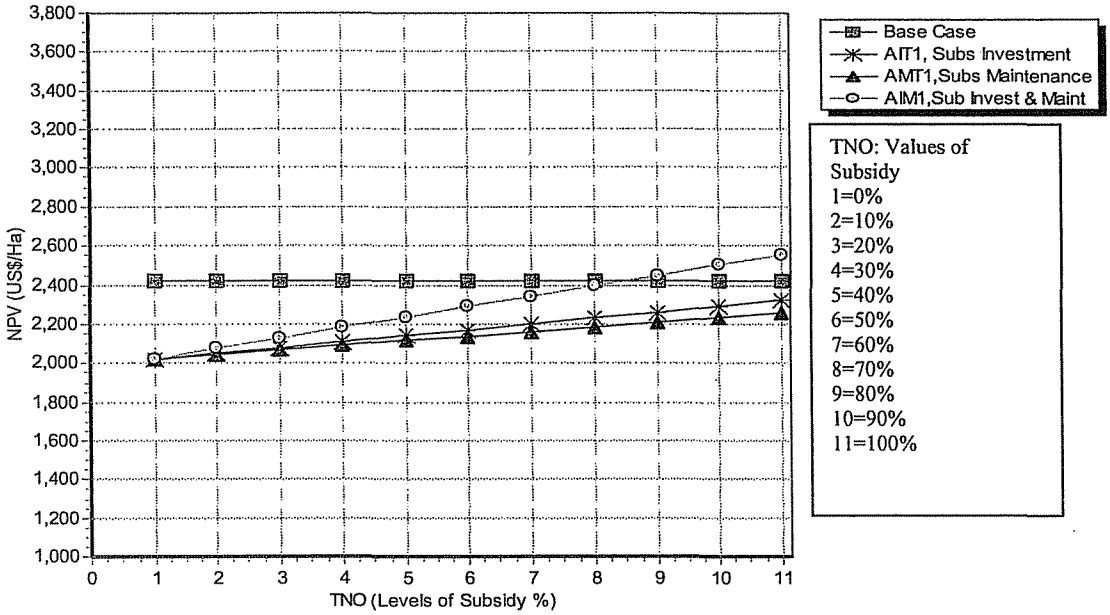
Figure 22: Scenario 5b: Time of Maturity of Terraces and Interest Rate.



AIR1 : Changes in interest rate for low productivity fields (BATPROD=25%) when TTIME=10
AIR2 : Changes in interest rate for low productivity fields (BATPROD=100%) when TTIME=10
AIR5 : Changes in interest rate for low productivity fields (BATPROD=100%) when TTIME=5
AIR6 : Changes in interest rate for low productivity fields (BATPROD=100%) when TTIME=5

For this scenario, TTIME is set at 5. The results are the same as in Scenario 3, that is, returns to investment on terraces are sensitive to the variables TERINV and TERMAN that represent the terraces investment and terraces maintenance costs respectively. However, the effect of TTIME is not sensitive to the different levels of subsidy as it is shown in Figure 23. Figure 18 is again included for purposes of illustration.

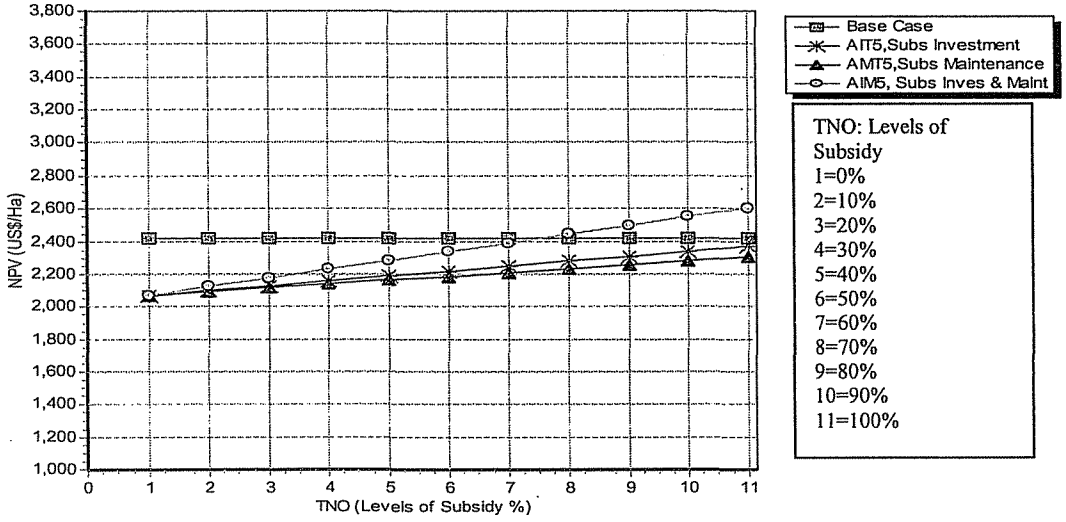
Figure 23: Scenario 5c: Time of Maturity of Terraces and Subsidies.



AIT1 : Subsidy in investment costs for low productivity fields
AMT1 : Subsidy in maintenance costs for low productivity fields
AIM1 : Subsidy in maintenance and investment costs for low

30

Figure 18. Scenario 3: Low Level of Productivity Effect and Subsidies



AIT5 : Subsidy in investment costs for high productivity fields when TTIME=5
AMT5 : Subsidy in maintenance costs for high productivity fields when TTIME=5
AIM5 : Subsidy in maintenance and investment costs for high productivity fields when TTIME=5

Economic Analysis of Terrace Investment

Understanding the economics of terraces in a spatially heterogeneous region such as the Andes requires analyzing the factors that affect the returns to terrace investments. As it was shown in the sensitivity analysis , several factors can affect profitability of terraces. Terrace investments are sensitive to interest rates, investment and maintenance costs, time to achieve maturity of terraces, and erosion and terracing effects on productivity.

In this section, terrace investments are analyzed from two perspectives: farm profitability and social value. Two policy instruments are considered. Capital markets (interest rate and access to financing) and subsidies for construction and maintenance of terraces.

It has been argued in this thesis that a fundamental fact of agriculture is *heterogeneity* in bio-physical and economic conditions. Location, discount rates, access to credit, physical features (e.g. soil characteristics and slope of their fields), levels of income (rich and poor farmers), and other characteristics make this heterogeneity a key factor to consider in policy making. An efficient (or first-best) policy to correct a market failure will take heterogeneity into account.

In the simulation model, physical heterogeneity is represented by the slope of farmers' fields. To represent the effects of slope on returns to terrace investments, we have stratified fields into two groups: high slopes (terraced fields with steeper slopes) and low slopes (terraced fields with lower slopes)[21].

[21] High Slopes: Fields with slopes greater or equal to 21%.

In the sensitivity analysis, the results were presented in terms of means. In this section the objective is to represent the degree to which terraces are profitable or not profitable, taking heterogeneity into account. For this purpose we define PNPV as the percent of fields with $(NPV_T-NPV_E)>0$, where NPV_T is the net present value for terraced fields and NPV_E is the net present value for an unterraced, eroded field. For this analysis, it is assumed that BAEPROD=60 for unterraced fields, implying that on average terraced fields lose about 40 percent of their productivity after 10 years.

Two policy issues are addressed. One is related to capital market distortions where high rates and limited access to credit are the main problems. The reasons for these problems are several: lack of collateral, high risk associated with crop production in this area; and high transaction costs (insufficient information regarding the ability to borrow funds, lack of local financial institutions).

On the other hand, externalities (on-farm vs. off-farm) are also a possible source of market failure. Farmers' lack of good information or knowledge about the long term consequences of the practices they adopt is considered as a source of on-farm externalities. On the other hand, in presence of externalities, private incentives are inadequate to address soil erosion problems due to the failure of considering external costs in private decision-making. Although it has not been measured in this study, soil erosion and excessive run-off on upstream fields of the La Encañada watershed may result in significant damages in croplands and water quality downstream. With unrestricted access or ineffective use of regulations, each farmer tends to use the resource up to the level where his marginal revenue is equal to the marginal cost of utilizing the

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Low Slopes: Fields with slopes less than 21%.

resource. It is crucial to know what kinds of fields are associated with externalities. Although proximity of fields to the surface water is a key factor determining impacts on water quality, the presumption in this study is that steeper fields generate higher erosion rates and greater externalities.

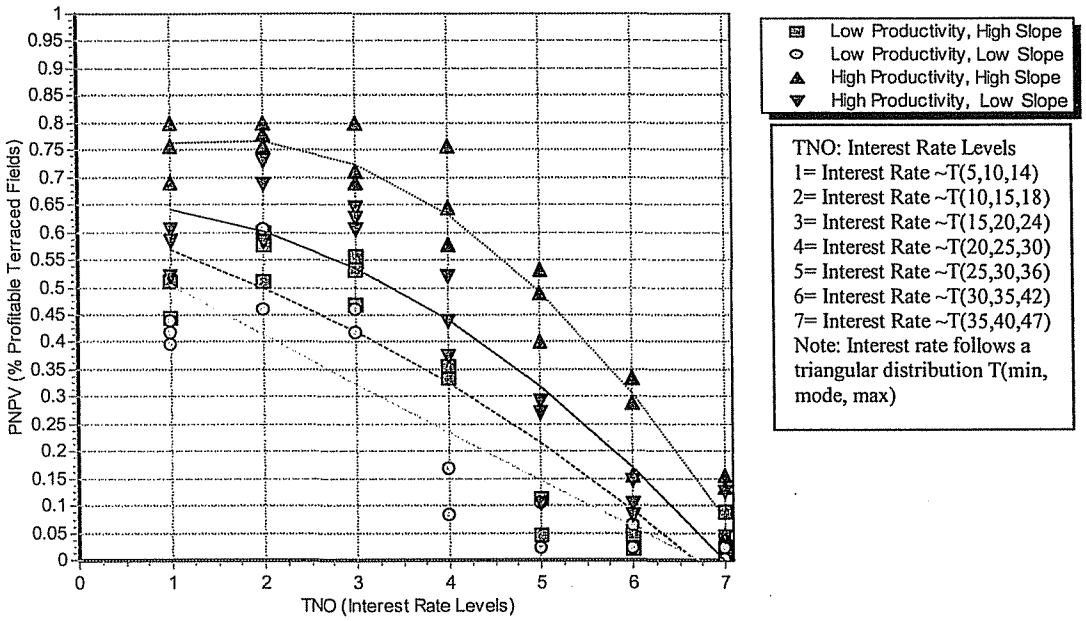
Results

Terraces Without Subsidies. Figure 24 shows that for the most likely case (high soil productivity, moderately high range of interest rates[22]), terraces are profitable for about 5% to 55% of the farmers in La Encañada. For interest rates in the range of 25% to 36% (TNO=5), terraces are profitable in about 40% to 55% of fields with high slopes, and about 10% to 30% of fields with terraces in less steeply sloped fields are profitable. These values are consistent with the survey data showing that about 28% of fields have some terraces.

Figure 24 also shows the profitability of terraces for low soil productivity levels. For the same range of interest rates (25% to 36%), terraces are profitable for less than 15% of the farmers with low productivity soils. With low interest rate values, about 60% to 80% of terraced fields with high productivity are profitable. On the other hand, about 40 to 50% of fields with terraces with low productivity are profitable.

[22] Market interest rates in Peru for 1997-2000 were about 22% to 31%. (PECC 2002)

Figure 24: Proportion of Fields With Profitable Terraces According to Slope, Productivity and Interest Rate.



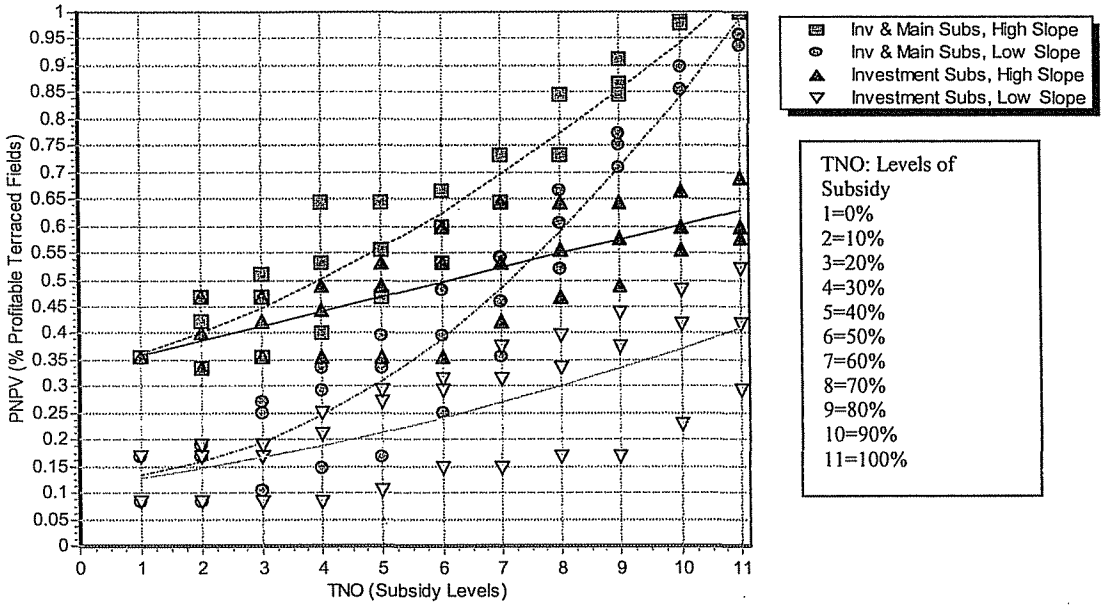
Terraces With Subsidies: Low Productivity Fields. Figure 25 illustrates the proportion of fields for which terraces are at different levels and types of subsidies. With no subsidy (TNO=1) about 8% to 18% of terraced fields with low slopes are profitable. About 33% to 38% of steeply sloped, terraced fields are profitable.

On steeply sloped fields, a 90% subsidy on investment and maintenance costs (TNO=11) makes terraces profitable on about 95% to 100% of these fields. A 100 percent subsidy on investment and maintenance costs is required to make terraces profitable on all fields with low slopes.

Figure 25 also illustrates the effect of subsidizing only investment costs. With a 100 percent subsidy of investment costs, about 55% to 70% of terraced fields with more

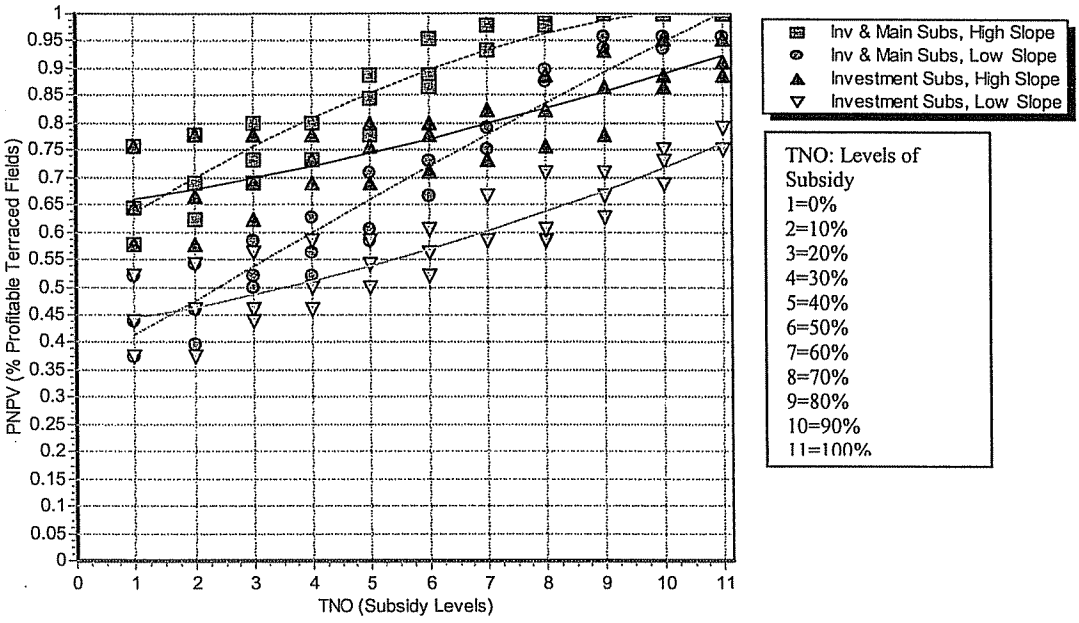
steep slopes are profitable. On the other hand, about 30% to 50% of terraced fields with low slopes are profitable.

Figure 25: Effects of Subsidies on the Proportion of Profitable Terraced Fields With Low Productivity.



Terraces With Subsidies: High Productivity Fields. Figure 26 shows the effects of subsidies under the assumption that terraces have relatively high productivity effects (BATPROD=200). A 70% subsidy on investment and maintenance costs will lead to the profitability of terraces on about 100% of steeply sloped fields. Only about 85 to 90% of terraces are profitable on less steeply sloped fields. A full subsidy on investment and maintenance is required to get about 95% to 100% of profitable terraces on less steeply sloped fields. On the other hand, with a 100 percent subsidy on investment only, about 85 to 95% of fields with terraces on steeper slopes are profitable to farmers, and about 75% to 80% of less steeply sloped fields with terraces are profitable to farmers.

Figure 26: Effects of Subsidies on the Proportion of Profitable Terraced Fields With High Productivity.

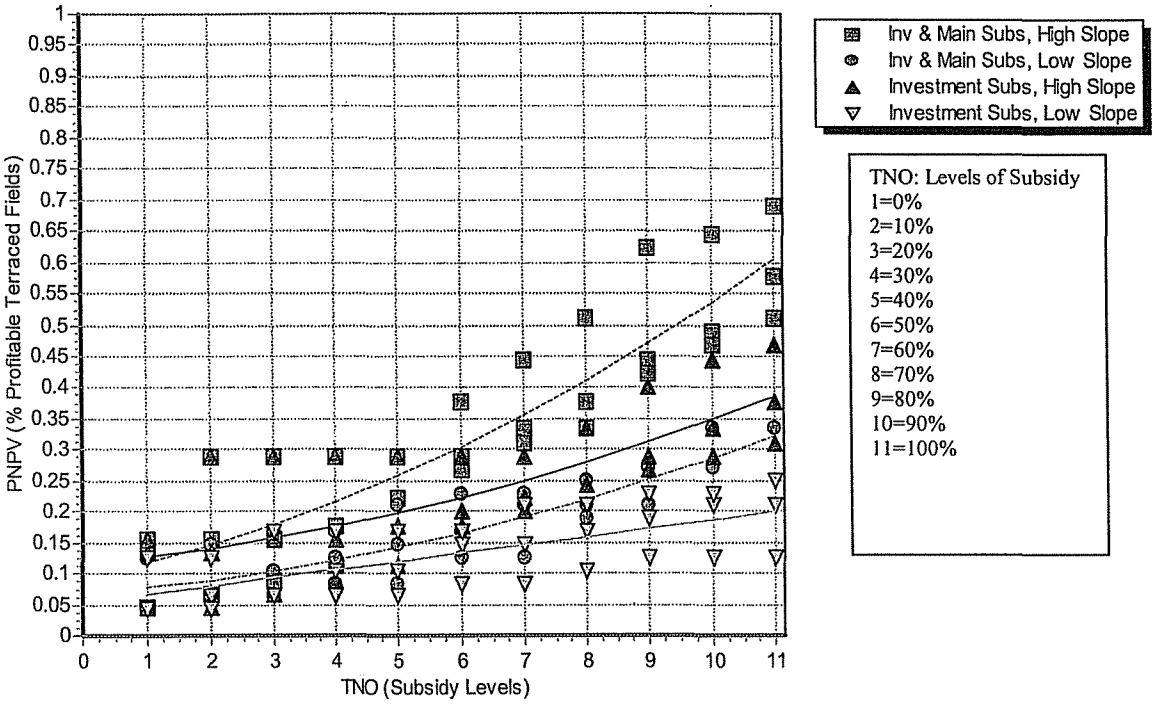


Terraces With Subsidies: High Productivity Fields With High Interest Rates.

Figure 27 illustrates the effects of subsidies assuming higher interest rates (in this case, interest rate ~Tri(35,40,47)) for high productivity levels. It is clear from the Figure that a high interest rate reduces considerably the proportion of profitable fields (see Figure 26 to compare). With this interest rate assumption, and with a full subsidy on investment and maintenance costs, about 50% to 70% of more steeply sloped fields are profitable to farmers. Also, with the same assumptions, about 30% to 45% of less steeply sloped fields are profitable for farmers.

A subsidy only in investment costs reduces the number of profitable terraces. With a full subsidy, about 30 to 35% of more steeply sloped fields are profitable to farmers, and about 10 to 25% of less steeply sloped fields are profitable to farmers.

Figure 27: Effects of Subsidies on the Proportion of Profitable Terraced Fields With High Productivity and High Interest Rates.



Summary of the Results

A summary of the results is shown in Table 13. From the previous analysis, it is clear that heterogeneity among farmers plays an important role in the economics of terraces. The results show that policies such as interest rate subsidies or subsidies for terrace construction and maintenance can have a substantial impact on farmers' decisions to invest in terraces. It has been argued in previous sections that farmers will adopt a conservation practice like terracing only if it is profitable for them. These results show that terraces may be profitable for some farmers but not for others due to bio-physical

and economic heterogeneity. It follows that subsidies should be targeted in order to account for the heterogeneity.

The analysis also shows that generally terraces are most likely to be profitable on steeply sloped fields. It has been argued that most of the externalities caused by erosion are likely to be associated with the most steeply sloped fields. Therefore, the analysis shows that without subsidies farmers will tend to invest in terraces where they are more socially efficient. However, it may be that there still is an under investment in terraces due to capital market distortions. The simulation shows that if the interest rate that farmers are paying is lowered, then at the margin, terraces may be more profitable for more fields with less steep slopes. The proportion of terraces needed to account for externalities was not measured in this thesis, and it would be necessary to have this information in order to determine the appropriate policy (subsidy, lower interest rate, etc.) to achieve the socially optimal quantity of terraces. . However, Table 14 shows hypothetical socially optimal quantities of terraces and the level of subsidy to achieve this optimal level. Subsidies are not needed for high productivity fields when the optimal quantity of terraces is low (30%). In low productivity fields with high slope, subsidies are not necessary if the optimal quantity of terraces is 30%. For low productivity fields with low slope, a subsidy on investment costs of about 70 to 80% or a subsidy on maintenance and investment costs, will reach the optimal quantity of terraces. If the optimal quantity is much higher (70%), then a 100% of subsidy on investment costs will not be enough to get the optimal quantity of terraces in low productivity fields. However, a subsidy in maintenance and investment costs of about 60% for steeply sloped fields and about 80%

for less steeply sloped fields will be required to achieve the optimal quantity of terraces. On the other hand, for high productivity fields, a 30% subsidy on investment costs will make 70% of terraced fields with high slope profitable. A 90% subsidy on investments will make 70% of the terraced fields with less steep slopes profitable. A 10% subsidy on investment and maintenance costs will reach the optimal quantity of terraces of 70% in steeply sloped fields. A 50% of subsidy in maintenance and investment costs will also make a 70% of the terraced fields on less steeply slopes profitable.

Table 13: Summary of Results from the Economic Analysis.

Figure	Case	Subsidy in Investment	Subsidy in Maintenance	% Subsidy	Productivity	Slope	Interest Rate	%Profitable fields (approx)
Figure 24	No Subsidy	NO	NO	0	HIGH	BOTH	MEDIUM-HIGH	10-55
	No Subsidy	NO	NO	0	HIGH	HIGH	MEDIUM-HIGH	40-55
	No Subsidy	NO	NO	0	HIGH	LOW	MEDIUM-HIGH	10-30
	No Subsidy	NO	NO	0	LOW	BOTH	MEDIUM-HIGH	<15
	No Subsidy	NO	NO	0	LOW	HIGH	MEDIUM-HIGH	5-10
	No Subsidy	NO	NO	0	LOW	LOW	MEDIUM-HIGH	<10
	No Subsidy	NO	NO	0	HIGH	BOTH	LOW	60-80
	No Subsidy	NO	NO	0	LOW	BOTH	LOW	40-50
	No Subsidy	NO	NO	0	HIGH	BOTH	HIGH	<15
	No Subsidy	NO	NO	0	LOW	BOTH	HIGH	<10
Figure 25	Zero Subsidy	NO	NO	0	LOW	LOW	MEDIUM	8-18
	Zero Subsidy	NO	NO	0	LOW	HIGH	MEDIUM	33-38
	With Subsidy	YES	YES	90	LOW	HIGH	MEDIUM	95-100
	With Subsidy	YES	YES	100	LOW	LOW	MEDIUM	93-100
	With Subsidy	YES	NO	100	LOW	HIGH	MEDIUM	55-70
	With Subsidy	YES	NO	100	LOW	LOW	MEDIUM	30-50
Figure 26	Zero Subsidy	NO	NO	0	HIGH	LOW	MEDIUM	40-55
	Zero Subsidy	NO	NO	0	HIGH	HIGH	MEDIUM	55-75
	With Subsidy	YES	YES	70	HIGH	HIGH	MEDIUM	95-100
	With Subsidy	YES	YES	70	HIGH	LOW	MEDIUM	85-90
	With Subsidy	YES	YES	100	HIGH	LOW	MEDIUM	95-100
	With Subsidy	YES	NO	100	HIGH	HIGH	MEDIUM	85-95
	With Subsidy	YES	NO	100	HIGH	LOW	MEDIUM	75-80
Figure 27	Zero Subsidy	NO	NO	0	HIGH	LOW	HIGH	5-12
	Zero Subsidy	NO	NO	0	HIGH	HIGH	HIGH	12-15
	With Subsidy	YES	YES	100	HIGH	HIGH	HIGH	50-70
	With Subsidy	YES	YES	100	HIGH	LOW	HIGH	30-45
	With Subsidy	YES	NO	100	HIGH	HIGH	HIGH	30-35
	With Subsidy	YES	NO	100	HIGH	LOW	HIGH	10-25

Table 14: Hypothetical Socially Optimal Level of Terraces and the Level of Subsidy Required.

Optimal Proportion of Terraces=>		30%		50%		70%	
Type of Filed	**Type of Slope**	**Investment Subsidy**	**Invest & Maint Subsidy**	**Investment Subsidy**	**Invest & Maint Subsidy**	**Investment Subsidy**	**Invest & Maint Subsidy**
Low Productivity	High Slope	0%	0%	50%	30%	>100%	60%
	Low Slope	70-80%	40%	>100%	60%	>100%	80%
High Productivity	High Slope	0%	0%	0%	0%	30%	10%
	Low Slope	0%	0%	30%	20%	90%	50%

CHAPTER 5

CONCLUSIONS

The objective of this thesis is to provide a better understanding of the economics of terrace investments in an important region of Peru and to determine whether returns to terraces are profitable or not. A method to conduct sensitivity analysis of an integrated assessment model was designed in order to conduct an economic analysis of the effects of terraces on productivity.

Results provide an insight into the economics of terrace investments and the important factors that affect returns to this investment. Results also provide a methodological approach to conduct sensitivity analysis with complex models.

This thesis demonstrates the importance of sensitivity analysis to understanding and interpreting the policy implications of integrated assessment models. For example, in the case study, significantly different policy implications are obtained about the need for terrace subsidies depending on key assumptions about terrace productivity and interest rates.

Most of the studies were very imprecise about the initial conditions (i.e. state of land erosion) to analyze the effects of terraces on productivity. This thesis demonstrates that initial conditions matter for the analysis of terrace productivity and have an important impact on the outcome.

Antle and Stoorvogel (2001), Thampapillai and Anderson (1994), Lutz et al. (1994), and others have hypothesized that it is important to account for heterogeneity in

the assessment of the economics of soil conservation. This thesis verifies the hypothesis that returns to conservation investments such as terraces are highly dependent on both physical heterogeneity (e.g., slope of fields) and economic conditions (e.g., interest rates and capital markets).

One of the most important problems in La Encañada watershed, as in many other regions, is soil erosion. Some efforts are taking place in this watershed to address this problem (e.g. incentives to build slow formation terraces). However, little quantitative information is available about the factors that cause it, or the effects of on-going policies. Few studies have addressed the economic, social, and institutional factors that affect farmers' land management decisions that in turn affect erosion. This thesis shows that in the conditions of northern Peru, terrace investments are potentially profitable for, and thus are likely to be adopted by, farmers on a significant number of fields. The likelihood of adoption increases with factors conducive to erosion (e.g., slope and related soil and climatic conditions). This study shows that terraces are most likely to be profitable on steeply sloped fields. Then, assuming that external damages to water quality are also positively associated with erosion rates, it follows that farmers will tend to invest in terraces with the highest private and social benefits. However, it does not follow that the optimal number of terraces will be built by farmers. To determine the optimal number of terraces, estimates of the external costs of erosion would have to be incorporated into an integrated assessment. Although the on-farm productivity effects of erosion and terraces studied here are believed to be the most important effects, a complete examination of terraces investments would require broader analysis that would include possible

externalities. This study provides the economic analysis that could be the foundation for a broader study that includes externalities.

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