Natural Resource Management in the Hillsides of Honduras

Bioeconomic Modeling at the Microwatershed Level

Bruno Barbier
Gilles Bergeron

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Foreword

Almost 2 billion people worldwide live on less favored or marginal lands, where they face increasing poverty, food insecurity, and environmental degradation. According to the pathways of development concept employed in this study, improving the standard of living in such areas is a function of a complex set of conditioning factors, the most fundamental of which is agroecology. In Honduras, one of the poorest countries in the Americas, most of the impoverished rural population lives on marginal hillsides. Previous IFPRI research in the central hillside region of Honduras identified five potential development pathways, including market-induced intensification of vegetable production on lands otherwise considered marginal and of low economic potential.

Barbier and Bergeron explore several hypotheses about the dynamics of natural resource management in the hillsides of La Lima and further explore the causes and consequences of the transition to vegetable production. To fully integrate agroecological factors, such as forest, water resources, and topography, the authors use a bioeconomic model that links farmers' resource management decisions to biophysical models. This captures production processes as well as the condition of natural resources. The model was used to run different scenarios over the period 1975 to 1995 and then to project into the future.

The authors conclude that agroecological conditions are the most important factors determining incomes for villages with comparable agroecological conditions. The simulations indicate that recent policy interventions, such as market liberalization, road construction, and crop improvements, have all helped to increase incomes. Roads, for example, provide better access to regional markets, allowing farmers to benefit from the advantageous prices offered for nontraditional crops. The study finds that incomes would have been much lower, and degradation much higher, if vegetable production had not been possible for ecological reasons, since farmers would then have been reduced to adopting less sustainable strategies.

Yet one strategy does not fit all. Keeping all else constant, it appears that alternative policies that one might assume to be beneficial, such as a land reform or developing dairy production, would probably not have been successful in La Lima. The authors thus demonstrate that the complexity of marginal environments must be fully considered before implementing policies because the same policy may have dissimilar impacts in different areas. The pathways of development approach can also help predict future outcomes of policy interventions and guide decisionmakers in targeting resources appropriately.

Per Pinstrup-Andersen
Director General

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Summary

The objective of this study is to simulate the effect of population pressure, market integration, technological improvement, and policy decisions on natural resource management in the hillsides of Honduras. To do so, a bioeconomic model was developed and applied to a typical microwatershed. The bioeconomic model is dynamic linear programming fed with data from a biophysical model. Over recent years, farmers from the selected microwatershed have followed a "vegetable intensification" pathway of development. Different scenarios were run with historical data over the period 1975 to 1995 and then projected 25 years into the future from 1995 to 2020.

The results of the bioeconomic model presented in this report aid the discussion of a number of induced innovation hypotheses. Many of our model's results conform with the hypotheses, but some of the results challenge conventional wisdom. The simulation results suggest that technology improvements such as irrigation and new varieties can help overcome diminishing returns to labor due to population pressure. Population increases in La Lima had only a small effect on the condition of natural resources because the cropped area increased only slowly thanks to the intensification of production. The model shows that the relationship between population growth and natural resource condition can have a U-shaped structure. In the long term, population pressure is likely to lead to continuing improvement in the condition of natural resources. The results also show that improvements in access to markets increase per capita incomes but do not necessarily promote land conservation because land values do not automatically increase. The hypothesis that agroecological conditions are the most important factors determining incomes and natural resource condition is illustrated by the results.

Past policy interventions such as market liberalization, road construction, construction of the potable water distribution system, crop variety improvement, and extension services have all helped to increase incomes. However, the simulations suggest that replacing inorganic fertilizer with organic fertilizers would not maintain incomes at the same level. Dairy production is a viable option. A land reform would have had a low but positive impact on incomes. The forward-looking baseline scenario suggests that erosion will continue to increase if prices remain as they were in 1995. If commodity prices decline, however, erosion will lessen because farmers will reduce their production of vegetables during the rainy season. Conversely, an increase in inorganic fertilizer prices will lead to more erosion because farmers will use less fertilizer, obtain lower yields, and increase their cropped area.

CHAPTER 1

Conceptual Framework

Population growth, market integration, and new technologies affect rural communities in many different ways, but a finite number of development pathways may be identified within homogeneous agroecological regions. A study by the International Food Policy Research Institute (IFPRI) of the Central Hillside region of Honduras empirically identified five different pathways (Pender, Scherr, and Durón 2001), one of which corresponds to market-induced transitions to intensive vegetable cropping. This pathway was considered particularly interesting because it illustrates the potential for intensive commercial agriculture in lands normally viewed as marginal.

The microwatershed of La Lima, located on the hillsides close to the capital, Tegucigalpa, was selected as a case study to facilitate understanding of the causes and consequences of this type of transition and to generate hypotheses about possible policy actions in similar contexts (Bergeron et al. 1997). The study covered a period of 20 years (1975–95) during which time the subsistence-oriented farming strategies that prevailed at the outset in that village evolved toward a semi-commercialized strategy including the production of vegetables using high-input practices.

This report shows how a bioeconomic model linking linear programming and a biophysical model is developed and used to examine the outcomes of this type of development over the past 20 years and the likely outcomes over the coming 25 years. Multiple scenarios are introduced that indicate the likely effects of specific measures on production, incomes, and environmental conditions.

The conceptual framework underlying this work is a stylized explanation of the mechanisms occurring in rural areas, and draws principally on the theory of induced innovation in agriculture (Boserup 1965; Ruthenberg 1980; Ruttan and Hayami 1990; Binswanger and McIntire 1997; Pingali, Bigot, and Binswanger 1987; Lele and Stone 1989; and others). Simply put, this theory argues that people endogenously adapt to changes in the conditions they confront, and that these adaptive responses are the main source of technical and institutional change in agriculture. Boserup used this idea to argue that population growth is the dominant cause of agricultural development in underdeveloped countries. The logic behind this proposition is that population growth increases the scarcity of land relative to labor, thus increasing the net return to intensifying labor use on a given piece of land by reducing fallow periods and investing labor effort in increasing land productivity. Boserup also argued that technological innovations (for example, adoption of organic fertilization) and institutional innovations (for example, development of private property rights), which are implicitly endogenous, are caused by population growth and resulting changes in land use.

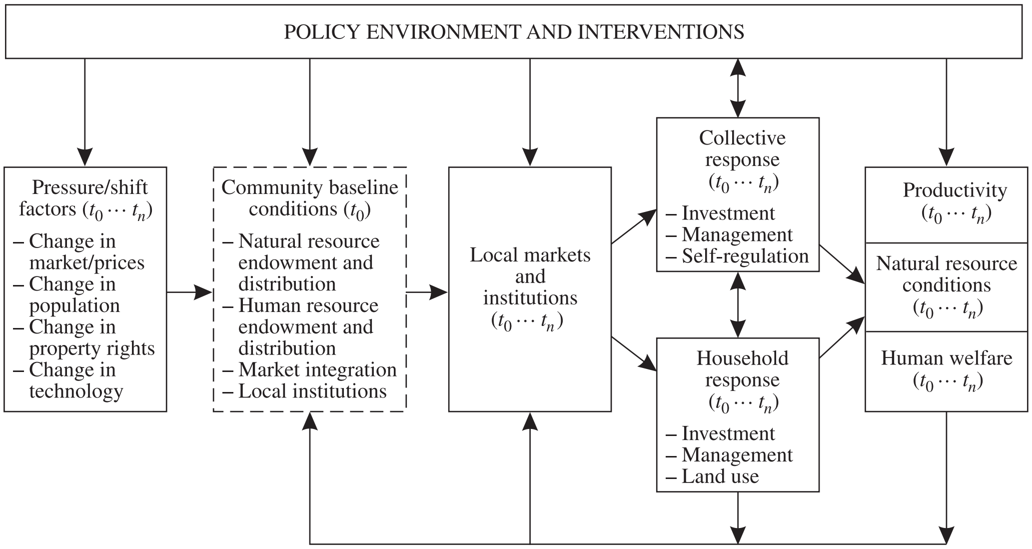
Other authors have expanded on Boserup's model by incorporating other exogenous factors that also stimulate endogenous agricultural change. Binswanger and McIntire (1997) and Pingali, Bigot, and Binswanger (1987) argue that increased access to markets, as may result from development of roads or other infrastructure, also causes agricultural intensification. Lele and Stone (1989) argue that government policies play an important role in shaping the nature and impacts of agricultural change, particularly the impacts on natural resources and the environment. Smith et al. (1994) argue that, because of diminishing returns to labor, exogenous technological advancement is necessary to avoid declining output per capita in the process of intensification, an argument reminiscent of neoclassical growth theory as pioneered by Solow (1974).

Our conceptual framework incorporates these exogenous (at the community level) factors of agricultural change under the term "pressure/shift variables" (Figure 1.1). Exogenous causal factors include the natural rate of population growth, changes in market access and development of markets for inputs and outputs, exogenous technological change (such as development of new crop varieties), and changes in government policies affecting property rights, land tenure, access to resources, prices, and other factors of agricultural production. These factors are the primary external drivers of change in a given community.

The impacts of these factors in a particular setting will be affected by local "conditioning factors" as shown in Figure 1.1. These include the community's resource endowments (land quantity and quality, forests and other vegetation, water resources, climate, topography, and other biophysical characteristics of the environment) and its "social capital" endowments (local institutions and organizations). These conditioning variables can be thought of as determining the constraints on decisions at the community and household levels.

The modeling described in this report follows this conceptual framework to simulate the aggregate behavior of farmers in the La Lima microwatershed. The model highlights population, markets, and technology

Figure 1.1 Conceptual framework



as the main forces driving change in agriculture. Accordingly, four hypotheses are postulated about the dynamics in natural resource management in the hillsides:

- Population pressure leads to greater total income but lower per capita incomes because of decreasing returns to labor.
- Population pressure has negative effects on natural resources until the productivity of the resource base declines to critical levels. Only then will farmers improve natural resource management.[1]
- Market access increases per capita incomes. Market access also promotes land conservation because land-value increases make investments in land improvements more profitable.
- Technological improvements have a significant positive effect on per capita incomes but an ambiguous effect on natural resources.

A fifth hypothesis verifies our assumption about the importance of agroecology in “filtering” outcomes at the local level:

- Agroecological conditions are important factors in determining incomes and resource conditions.

The model will aid the discussion of each hypothesis.

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[1] This process can be represented by a U-shaped function where the natural resource stock decreases to the point where farmers start to invest in its enhancement (Scherr and Hazell 1994).

CHAPTER 2

Agriculture in Honduras

Honduras is one of the poorest countries in the Americas, with a gross domestic product (GDP) of US$640 per capita (World Bank 1997). The economy relies heavily on agriculture, which generates 70 percent of total export earnings and employs 58 percent of the labor force (World Bank 1997). Slopes greater than 12 percent account for 85 percent of the landmass, and the spatial distribution of land is as follows: the fertile lowlands and valleys are owned by large farmers, ranchers, or international fruit companies, while the majority of the rural population lives on hillsides. Population growth is rapid, and some view this as the main cause of deforestation and erosion (Silvagro 1996). It is estimated that soils have experienced moderate to strong degradation on 10–25 percent of the hillsides of the region (Olderman, Hakkeling, and Sombroek 1990), and that erosion ranges from 9 to 50 metric tons per hectare per year on slopes of 15–40 percent (Wouters 1980). Various sustainable cultivation techniques have been developed for such environments, but their adoption is low in Honduras (Bunch and López 1995; Pender and Durón 1996; Valdés 1994; Léonard 1989).

Studies of recent agricultural policy in Honduras usually distinguish between three distinct periods (Durón and Bergeron 1995). Until 1980, industrialization, driven by import substitution, favored the urban zone to the detriment of agriculture (Williams 1986). Beginning in the early 1980s, the government abandoned this strategy and focused instead on increasing agricultural exports, mainly of high-value crops such as fruit, cattle feed, and shrimp. Those policies were expanded in 1989 with the adoption of a structural adjustment program, which removed most tariffs and barriers to international trade. This favored local producers, as a higher exchange rate promoted exports and reduced imports.

These demographic, economic, and policy changes have had diverse effects on rural areas. In a study of the Central Hillside region of Honduras, five distinct pathways of change were identified: (1) the extension of maize production; (2) the intensification of vegetable production; (3) an increase in coffee production; (4) the intensification of livestock production; and (5) the intensification of forest product extraction (Pender and Durón 1996). This study was undertaken in La Lima, a microwatershed located close to the capital city and viewed as representative of the "vegetable intensification" pathway.

CHAPTER 3

The Microwatershed of La Lima

Data were collected in the microwatershed of La Lima from January 1995 to October 1997, as follows:[2]

1. A household census was conducted detailing land, labor, capital, livestock, trees, access to water, and on-farm and off-farm activities (Bergeron et al. 1997).

2. Twenty households were interviewed in-depth to determine incomes, expenditures, consumption, and investment, as well as crop and livestock budgets.

3. Aerial photographs of the microwatershed from 1955, 1975, and 1995 were analyzed to determine current and past land use patterns. The aerial photographs were digitized and imported into geographical information system (GIS) software to analyze spatial patterns of land use, soils, and topography.

4. A history of plot and farm changes over the 20 years from 1975 to 1995 was undertaken based on recall interviews with farmers (Bergeron and Pender 1996).[3]

5. Price time-series data were collected and information on the evolution of the market structure was elicited from key informants (Mendoza 1996).

6. Detailed soil analysis was performed (Eriksen 1996); erosion was monitored on one representative cultivated plot; and water flows and sedimentation were measured during one entire rainy season (Tamashiro and Barbier 1996; Flores Lopez 1996).

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[2] Data collection was a collaborative effort between the Escuela Agrícola Panamericana of Zamorano, Inter-American Institute for Cooperation on Agriculture (IICA), and IFPRI.

[3] The plot history method consisted of randomly selecting 100 points within the microwatershed. For each point, the owner of the plot was asked to recall the land use over the past 20 years. The quality of the recall declines with time, but the results are similar to aerial photography from 1975.

General Characteristics

The microwatershed of La Lima covers approximately 10 square kilometers. Only 18 percent of the microwatershed has land with slopes under 15 percent; 52 percent has slopes of over 30 percent. The microwatershed is typical of the hillsides of Central America with respect to its soils, altitude (1,000–1,800 meters), and climate (bimodal rainy season with mean yearly rainfall of 1,200 millimeters). Production systems are also typical of Central America, with mixed farming of vegetables, maize, coffee, and livestock. Most of the land is under extensive use: pine forests dominate (25 percent of the area), followed by pastures (21 percent), and mixed pastures and trees (20 percent). Fallow land occupies 17 percent and the permanently cultivated area covers 14 percent. This land use did not change much over the 20-year period. Pastures have remained almost constant because major owners prefer large ranching over cultivation. Forests, mainly located on steep slopes, also remained largely unaltered. The main change was the development of intensive irrigated cultivation of vegetables but the area affected has remained relatively small.

In 1995, the microwatershed supported 507 inhabitants living on 80 farms. Between 1975 and 1995 this population increased at a mean rate of 2.5 percent per year. Although the current population density is low in absolute terms, at 56 inhabitants per square kilometer, it is high compared with the Honduran average of 26 rural inhabitants per square kilometer.

The average income in 1995 among a sample of 20 farmers was US$800 per worker[4] and the average daily income was higher than the official daily minimum wage of US$1.20.[5] However, income variations were large: only 30 percent of the workers earned more than the community's average; 10 percent had an agricultural net income per worker three times higher than the average. Detailed expenditure data show that only 40 percent of the interviewed farmers made any agricultural investments in 1995. Property acquisition accounted for 70 percent of investment and oxen acquisition for 19 percent. There were no reports of investment in cattle, calves, or conservation practices, and lower-income households did not purchase chemical inputs.

Labor is a limiting factor in La Lima. The average family farm has 1.7 workers but, since women work little in agriculture, the average consumer/producer ratio is only 0.3. Extended families with several married adults within the household are rare. However, collaboration between family members remains high, especially through share-cropping practices: 50 percent of the vegetables and a sizable proportion of the maize grown locally are produced under share-cropping arrangements. These help farmers pool labor, land, and capital, and also provide an effective strategy for minimizing risk.

The labor market is active in La Lima: 60 percent of all farms employ paid labor during peak periods at an average of 40 days per farm per year. Wage labor is the primary source of income for 25 percent of the workers, and is a secondary activity for 8 percent of the workers. Temporary out-migration is rare, probably because demand for labor is high in the microwatershed. Returns to labor in farming in La Lima compare favorably with typical unskilled wage levels in the nearby capital city. This helps explain the low rates of out-migration in recent years.

Formal land titling is still rare in the community, and land is usually held in usufruct. The market for usufruct rights is active, particularly within kin groups. Of all the plots currently used by farmers, 66 percent had been purchased, usually from parents, whereas only 33 percent were inherited.

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[4] The fraction of production directly consumed by the family is not included.

[5] The four largest ranchers of La Lima were not included in the sample of 20 farmers from whom detailed consumption and expenditure data were collected.

The capital market is deficient in La Lima. There is no formal credit and farmers appear reluctant to use the informal credit market. In 1995, the informal real interest rate in a neighboring community was between 0.97 and 2.47 percent per month, giving an annual rate of between 11 and 30 percent. Saving rates being low and inflation high, farmers prefer to reinvest their surplus in land.

Maize Production

Maize is the most important crop in terms of area in La Lima. The average maize yield is 2.1 metric tons per hectare, which is higher than the national average. This above-average performance is apparently due to the adoption of new varieties and the increasing use of inorganic fertilizers. Maize production does not require pesticides because pest damage is low. Farmers generally plow their maize fields using hand tools but, if the topography allows, they may also use a traditional plow pulled by two oxen. Small farmers produce maize mainly for consumption purposes, whereas ranchers have larger fields of maize for sale that are sharecropped with small farmers.

Vegetable Production

Farmers from La Lima were already producing vegetables in the 1960s (particularly potatoes), but the production of vegetables intensified and diversified rapidly after the opening of an all-weather road in 1985. Until then, farmers had to carry their produce by mule to the nearest road, located 6 kilometers from La Lima. In 1993, the La Lima road was improved and intermediaries now come to buy vegetables directly from the community. Vegetables are produced by 85 percent of the farmers, and represent 75 percent of farmers' cash income. Potatoes and onions are the main commercial crops. During the dry season, irrigation is required but installation costs are low, especially since the government installed a potable water system that some farmers tap for their production needs. Pesticide and inorganic fertilizer use has increased rapidly with vegetable cropping, but analysis by the Escuela Agrícola Panamericana (Panamerican Agricultural School) of Zamorano found no trace of contamination in the water or soils of La Lima.

Livestock Production

Cattle ranching is relatively important in La Lima. In 1995, there were 486 head of cattle, or one per person. This is similar to the Honduran average (FAO 1997). Cattle density is low, at 0.6 animals per hectare for the whole microwatershed, but there is considerable variability in this figure because of the heterogeneity of pastures. Pastures are found both on sloped areas and in some waterlogged flat areas. Some areas were overgrazed, and large grazing areas were found to be invaded by shrubs. Forests are also frequently used for grazing animals. In addition, farmers let livestock graze on maize residue during the dry season, partly because of the shortage of forage during the dry season but also to increase soil fertility through manure deposits.

Local ranchers usually keep their female calves and sell the males to ranchers in the valley, or locally as oxen. A small local market for milk and cheese has developed but production is low: the local breed produces less than 700 liters of milk per cow per year.

Natural Resource Management in La Lima

Water Management

Water in La Lima is relatively abundant and in 1993 the government installed a potable water distribution system in the lower part of the microwatershed. As part of this study, water volumes were measured using a flow meter at different locations within the microwatershed to assess existing and future water shortages (Tamashiro and Barbier 1996). In April 1996, at the end of the dry season, the springs of the microwatershed produced 869 liters per minute. Of this, 16 percent was captured by the potable water distribution system, 56 percent was used directly by individuals, and 26 percent was left for downstream users. The remaining 2 percent was lost in evaporation.

Access to the main streams is unequal: 10 percent of the farms in the microwatershed own 51 percent of the total irrigated area and 56 percent of the total water is captured by those few individuals whose fields have access to the stream. These individuals hire farmers who do not have access to the stream as wage laborers (260 days of wage labor per farm per year, which is six times more than the village average). Additional water could be used by the community to increase the irrigated area by 20 or 30 percent, but this would increase water scarcity for the downstream users. Vegetable producers who live downstream of the microwatershed have already had to reduce their production drastically owing to the increasing water use in La Lima (Mendoza 1996).

Forest Management

The forest consists mainly of pine trees and some patches of broad leaf trees. Aerial photo comparisons show that the forested area was reduced between 1955 and 1975, but stayed almost constant between 1975 and 1995. Three hypotheses may be suggested to explain the maintenance of tree cover in that period. First, the Forestry Law of 1973 gave control over national forests to Corporación Hondureña de Desarollo Forestal (Honduran Corporation of Forestry Development), a government agency, which took away cutting permits from local farmers. Second, most of the forest remaining after 1975 was located in areas with slopes greater than 30 percent and was therefore too difficult to cut. Third, many of the forests in the microwatershed are used for grazing. Large ranchers have taken advantage of the fact that forest ownership is poorly defined and acquired de facto control of large areas of forested land that they do not officially own. These areas are still considered to be forest, even though their tree density is low and continues to decrease because of cattle grazing.

Soil Nutrient and Organic Matter Management

Subsoils in La Lima are basaltic and rhyolitic and are part of the Ojojona soil series that is common in Honduras (Canales 1994). Of 243 soil samples selected randomly, 49 percent were classified as loamy clay, which is soil with more than 28 percent clay content (Eriksen 1996). The clay content and the kaolinite nature of this soil makes for poor drainage. Because these soils become waterlogged when it rains, and compact after a few days without rain, they are difficult to plow. Farmers in La Lima classify their soils according to texture and fertility (Ardón 1996), but they do not consider soil characteristics to be important factors in crop choice, because they see them as relatively homogeneous throughout the microwatershed.

The soils are acid, with a pH of about 5 (Eriksen 1996). The soil analysis, compared with the norms of the soil laboratory of the Panamerican Agricultural School at Zamorano, suggests good soil nutrient management in the cultivated plots, with no major phosphorus, potassium, or nitrogen deficiencies.

Soil fertility management has changed over time in La Lima. The traditional technique was based on fallow cycles, alternating livestock rearing with crop production, and using slash and burn techniques to perform periodic clearing. Now, 90 percent of farmers use chemical fertilizers, and slash and burn has been abandoned. On 30 percent of the cultivated plots, maize residues are grazed and incorporated into the soil. No manure is applied other than that left by roaming animals.

Erosion Management

Erosion was measured on one representative maize plot (160 meters long) using the “nails and washer” technique (Burpee 1997) during the rainy season of 1996. The average slope on the plot was 25 percent, and erosion measured 4 millimeters. With a soil density of 1.4, this translates into an erosion rate of approximately 56 tons per hectare. Such a rate, although not statistically representative and probably not sustainable in the long term, is what one might expect given the characteristics of this plot, and so we use it as indicative of soil loss rates in La Lima. Measuring sedimentation at the margins of the microwatershed, a rough extrapolation suggests an erosion level of 6 tons per hectare for 1995 for the entire microwatershed (crop, pasture, and forest).[6] This level is low for hillside conditions, but possible given the relatively good soil cover within the microwatershed.

Accordingly, farmers in La Lima do not perceive soil erosion as a threat. They are more concerned about the lack of rain and about water-logging of the soil than about erosion. There is evidence that farmers even prefer to plant maize on slopes: 29 percent of the total maize area is planted on slopes greater than 30 percent, and 34 percent is planted on slopes of 15–30 percent; only 36 percent is planted on areas with a slope of less than 15 percent. This situation does not seem to be due to limited access to flat areas by small farmers because even large ranchers cultivate maize on slopes and keep flat areas for productive pastures.

Few techniques have been adopted to control erosion in cultivated areas despite persistent efforts by extension services.[7] The main methods are stone walls, found on 15 percent of plots, and contour plowing, used on 14 percent of plots. Live barriers, terraces, tree planting, and drainage ditches are rare. Soil erosion is reduced by three other means:

1. Weeds in the maize field reduce runoff.

2. Almost all plots are fenced with stone walls, hedges, or barbed wire and the eroded soil accumulates behind these fences or at the lower end of the fields. In the long term this creates a relatively terraced landscape, which characterizes the microwatershed today.

3. Plots are small and water flow does not have time to accelerate within the field.

These traditional techniques, common in Honduras, are not explicitly used to reduce erosion but are effective and should be considered as part of microwatershed management.

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[6] These numbers should be treated with caution because soil erosion is an irregular process that occurs during a few rain events in the course of a year.

[7] For a review of soil conservation experiences in Central America, see Lutz, Pagiola, and Reiche (1994) and Sims and Ellis-Jones (1994). For a review of agroforestry in Central America, see Current, Lutz, and Scherr (1996).

CHAPTER 4

Modeling Method

Linear programming has been widely used to predict the supply response and farmers' incomes under different agricultural policy scenarios (Hazell and Norton 1986). More recently, a new type of model, called a bioeconomic model, has been developed. A bioeconomic model links mathematical programming formulations of farmers' resource management decisions to biophysical models that describe production processes as well as the condition of natural resources. The objective is to address both agricultural production and environmental concerns. In developed countries, these models focus on environmental pollution, whereas in developing countries the focus is on land degradation.

The development of bioeconomic models in developing countries has been slow because the situation is more complex than that in developed countries. First, farming systems in developing countries are less specialized and tend to combine a larger range of interlinked activities such as crops, livestock, forestry, and off-farm activities (Ruthenberg 1980; Beets 1990). Second, most farming systems in developing countries include livestock and tree management. Modeling these activities necessitates the use of a dynamic framework and requires information about the length of the planning horizon, the discount rates, the returns to investment, the depreciation of capital, and loan repayments. Third, the farming systems of developing countries rely more directly on the condition of local natural resources than on external inputs. Natural resource conditions result from complex biophysical processes that are difficult to quantify. Fourth, it is more difficult to validate accurate bioeconomic models in developing countries because land degradation has a stronger impact on yields. Because this impact was not well known, productivity modeling was not accurate. Several linear programming models for simulating land degradation have recently been developed, including variables such as soil erosion (E. Barbier 1988) and soil nutrient or organic matter depletion (Parikh 1991; Kruseman et al. 1995; Barbier 1998). Fifth, natural resource management in developing countries usually includes problems that go beyond farm boundaries. This feature has been included in recent community-level models (Kebe et al. 1994; Taylor and Adelman 1997; Barbier and Benoît-Cattin 1997). Finally, rapid changes in population and markets in developing countries limit the value of static analysis.

The Linear Programming Model

In response to the above challenges, a bioeconomic model was developed for the La Lima community that is both dynamic (with a five-year planning horizon) and recursive (over the 45-year period 1975–2020). The model, designed at the microwatershed level,[8] includes two social groups (ranchers and small farmers), who are spatially disaggregated by nine different segments in the landscape (defined by topography and soil type). This gives 18 farm submodels within the community model. Farm submodels interact through seasonal labor markets. The model includes soil erosion and dynamic interactions with livestock, crops, and forest. Yields and erosion parameters are given by the biophysical Erosion Productivity Impact Calculator (EPIC) model developed by Williams, Jones, and Dyke (1987).

The model maximizes the aggregate utility of the whole microwatershed over a five-year planning horizon.[9] Utility is defined as the discounted value of future net monetary incomes plus the closing value of livestock and trees, plus the value of leisure taken. Leisure is valued using a fixed reservation wage, and a 15 percent discount rate is assumed in the baseline scenario. A sensitivity analysis showed that changes in the discount rate had only modest effects on land use.

The model maximizes aggregate utility for the entire community. This approach gives the same solution as if optimizing each of the individual farm submodels separately, subject to the common labor market constraints, providing there are no externality problems cutting across farm subgroups. If such externalities exist, this would lead the aggregate model to achieve a higher value of utility than is possible when the submodels are solved separately. We shall return to this issue after describing the structure of the model in more detail, but our general conclusion is that serious externality problems do not arise in the model given the way we have formulated it.

Although the model is dynamic and optimizes over a five-year planning horizon, it is also solved recursively each year to generate a series of annually updated plans. This is done 20 times for the period 1975 to 1995 and 80 times for the period 1995 to 2075. In this framework, the optimal solution for the first year of the planning horizon becomes the initial resource constraint of a new model that is solved for the following five-year period, and the process is repeated each year. The resources carried over in this manner are population, livestock, tree volume of different aged trees, soil depth, soil conservation structures, and plows. The recursive method allows us to track much longer periods than the five-year planning horizon, and to shock the model each year for exogenous changes in prices. Note that technological parameters and prices are the actual exogenous parameters prevailing just before the planning period, and these are maintained over the planning horizon. The key assumptions of the modeling process are described in the following section (a full description is in the Appendix).

Population and Labor

The available farm family labor in the watershed is constrained by the active population residing there each year. The number of residents is given exogenously and follows from projections of population growth and permanent net migration out of the village. Farmers can hire or sell seasonal labor both within and outside the watershed. These transactions are defined in day units, and encompass labor transactions between the different subgroups within the watershed, the hiring in of day labor from outside the watershed, and the selling of community

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[8] For microwatershed-level analysis, see Thurow and Juo (1995), as well as Inter-American Development Bank (1995).

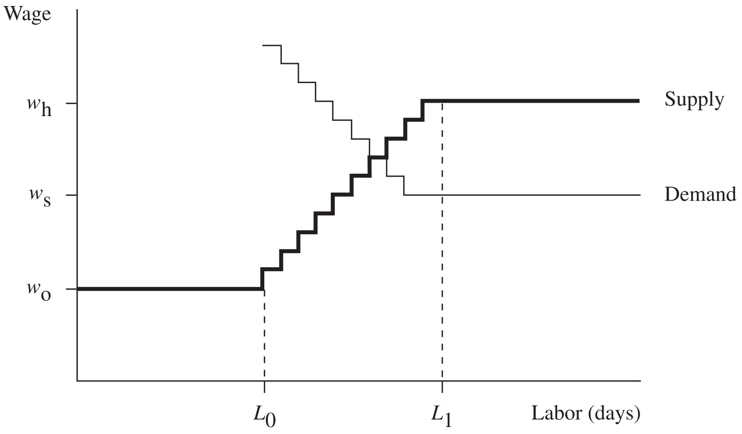
[9] The program is written in General Algebraic Modeling System (GAMS) (Brooke, Kendrick, and Meeraux 1988).

labor outside the watershed. Transactions outside of the watershed occur at exogenously given wage rates, whereas those within the watershed are driven by the shadow price of labor in each season, which is endogenous to the model.

The supply of labor each season within a submodel comprises a stepped approximation of a conventional upward-sloping function (Figure 4.1). The cheapest source of labor is own-family labor at a wage equal to the reservation price of leisure (w_r). This price is fixed at 80 percent of the local wage rate. Once all the own-family labor has been employed (L_0), then the next least-cost source of labor is to hire workers from other farms (submodels) in the community. The price for this labor is determined endogenously in the community labor market. However, because workers can be brought in from outside the community at a fixed wage (w_h), the endogenous wage for family labor transactions within the community cannot exceed that wage, nor can it fall below the reservation value of leisure. Once all the available community workers are employed, at L_1 (where L_1 is total family labor in the community), then the final source of labor is to bring in workers from outside at an exogenously given wage (w_h). These three sources of labor define the three segments in the labor supply function in Figure 4.1. Note that the middle segment is not a single step but comprises lots of little steps that depend on increases in the opportunity cost of labor in other community submodels. The number and length of these steps depend on the complexity of the model and the number of basis changes that occur in the solution as the wage rate increases (see Hazell and Norton 1986, Chapter 7).

The aggregate labor supply function for the community is simpler, comprising just two steps (Figure 4.2). The first step is the aggregate supply of family labor (L_1) at the reservation wage (w_r) or above. The second step is the supply of outside labor at wage w_h.

Figure 4.1 Labor market for a submodel



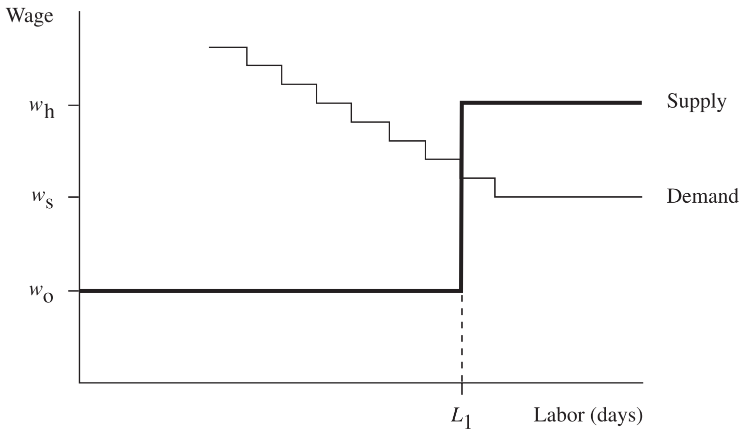
The demand functions for labor are also shown in Figures 4.1 and 4.2. In each case it is a step function approximation and, as in any linear programming model, comprises a series of steps, the number and length of which are determined by basis changes in the model solution as the wage is increased. Both functions become perfectly elastic at wage w_s, the wage at which community workers can sell their own labor outside the community.

The labor market equilibrium for the community always leads to a wage that falls within the range w_0 and w_h. If the labor demand intersects the supply function at either w_0 or w_h, then the wage rate will in effect be exogenous to the model. But if the intersection occurs between these two values, then the wage is determined endogenously and is equal to the shadow price of labor. There are four seasonal labor markets in the model, each of which has the structure just described.

The Division of the Microwatershed

The simulated microwatershed is delineated into three zones based on altitude. The objective of the disaggregation is to assess the effect of water use by one zone on the zone located below. Springs are used for human, livestock, and crop consumption.

Figure 4.2 Labor market for the community



The unused water runs out of the microwatershed. The first zone, which is located above 1,500 meters, benefits from a limited amount of water during the dry season and is controlled by a few ranchers. The zone located between 1,350 and 1,500 meters has an irregular topography, but benefits from several abundant springs during the dry season. The lowest zone, between 1,100 and 1,350 meters, is flatter and benefits from good access to the main stream of the microwatershed.

Each zone has a different initial endowment of three types of soil with varying slopes, soil depths, and productivity. Each zone is managed by two groups of farmers—the small farmers and the ranchers—with different initial population densities. Three zones, three types of soil, and two groups of farmers lead to 18 land units. The optimal choice of land use for each of the four seasons is a combination of forest, pasture, crops, and land conservation structures. Each zone is located at a different distance from the main road and from the other zones, giving rise to varying transportation costs in terms of time from zone to zone.

This spatial definition and disaggregation of the watershed also avoids any major problems with externalities that could cut across the 18 submodels and invalidate use of a single maximand for the entire community. Soil erosion is tracked for each subsection of the watershed, and the model does allow for erosion to affect yields within the subsection in which it occurs. Movement of soil and associated plant nutrients largely stays within the subsection in which it occurs (because of contouring, fencing, and so on) and moves from the cropped to the non-cropped area. The soil and nutrient runoff that does escape exits via streams that carry the soil out of the watershed entirely. Since the runoff is not deposited in neighboring sections of the watershed, this externality does not affect the model solution.

Water flows within the watershed are more complex. Because there are springs in the upper segments of the watershed that feed the main stream that passes through the community, water use by farms in the upper watershed during the dry season has an impact on the amount of water available for irrigation by other farms in the community. This is potentially a problem for the model because maximization of aggregate utility for the community will lead to rational allocation of this water between different submodels, even though this would not occur if the utility of each submodel were maximized separately. Fortunately, the problem may not be very serious. In the first place, the springs in question supply only a small part of the total water passing through the main stream. Second, not all the water in the stream is used by the community anyway; as reported in Chapter 3, about a quarter of the water is allowed to pass downstream for use by other communities, even in the dry season. Third, there is evidence that the community has taken some steps to solve this problem in a rational way. There seems to be an informal rule prohibiting any one farmer from taking excessive amounts of water for irrigation, and farmers downstream have successfully lobbied in the past to stop other farmers from overusing the springs in the upper watershed.

Another potential externality problem is pesticide contamination of water supplies. However, a study by the Zamorano Panamerican Agricultural School found no trace of agricultural pollutants within the watershed. The real problem is contamination of the water that flows out of the La Lima community to other communities downstream. Although this is a serious externality problem, the damage is caused outside the area encompassed by the model and hence does not affect the validity of the model's objective function for simulating farmers' behavior.

Crop Production

The model offers a selection from four crops: maize, potatoes, onions, or tomatoes. Onions are produced during the dry season, maize and tomatoes are produced during the first rainy season, and potatoes are produced during the second rainy season. The model also distinguishes four labor periods: the dry season, the first half of the first rainy season, the second half of the first rainy season, and the second rainy season.

The crop production function in the linear programming model represents the average expected response to different factors of production. The production functions are linear-segmented approximations of nonlinear functions.[10] The production functions are specified for each type of crop, each zone, each type of soil, each type of farm, and each year of the planning horizon. The total production of each crop is an average yield multiplied by the cropped area, with the effects of the amount of organic and inorganic fertilizers used and of plowing instead of hoeing added, and the effects of inadequate irrigation during the dry season, soil erosion, and insufficient soil depth subtracted. The effects are non-linear and are approximated by linear segments. An exogenous parameter that varies the response to organic and inorganic fertilization enables the model to simulate the effects of crop variety improvements over time.

Product Allocation

The marketing of vegetables is constrained in the model. In the 1970s, most farmers from La Lima could not produce vegetables because they did not have marketing outlets. Only a few farmers who had special ties with the few traders who came to the closest town were able to sell. This is reflected in the model by constraining the sales of products during the first years of the simulation. This constraint is progressively relaxed over time to reflect an increasing demand for vegetables, and after 1985, when the road was built, the constraint is removed altogether.

In the model, maize may be stored, consumed by the population and livestock, or sold during each season of the year, with different activities programmed for each season. The population consumes a fixed amount of grain during each period. Grains may be produced by the household or bought. The model seeks the best moment to sell, buy, and store grain depending on seasonal prices and family grain needs.

Livestock Production

The model simulates the size and management of herds of cattle, oxen, and mules that are owned by the small farmers and ranchers. Herd growth is determined by weight gain and by birth and mortality rates. If it is economically attractive, cattle can be bought or sold. Each livestock unit requires labor time, veterinary expenses, and forage throughout the year. Oxen are used for land preparation, mules for transportation, and cattle for producing milk, which is sold in some scenarios or is consumed on the farm.

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[10] A complete development of the equations is available in the Appendix.

The quantity of forage produced by pastures differs by season, by type of soil, and by altitude. A fraction of the unused forage is carried over from one season to the next. Livestock can also be fed with crop residues and with purchased feed. Cattle access to pastures in the microwatershed is controlled by market transactions in the form of grazing fees.

Soil Erosion

Soil erosion per hectare is modeled as a function of the area of each crop and the presence or absence of conservation structures. Erosion can affect yields in two ways. First, runoff affects yields by reducing the amount of nutrients and water available to the plant (this loss is referred to as the "nutrient effect"). Second, erosion cuts yields by diminishing soil depth, which reduces root growth once a minimum soil depth is reached (the "soil depth effect"). The linear programming model, based on the data generated by EPIC (Tables 4.1 and 4.2), shows how the nutrient effect is captured simply by specifying that yields decrease as a function of the quantity of soil eroded. Modeling the soil depth effect is more complex. In each of the 18 land unit areas, there are two initial volumes of topsoil, one planted with crops and one under forest, grass, and soil conservation. There is much less erosion under forest, pastures, and soil conservation structures than under crops. Over time, the soil volume under crops decreases whereas the soil volume under pastures, forest, and soil conservation structures remains constant. However, when the model expands the cropped area at the expense of the noncropped area, soil volume is transferred from the noncropped area to the cropped area. Conversely, when the cropped area is abandoned, a transfer of soil volume occurs from the noncropped area to the cropped area. This transfer provides for the possibility of abandoning cultivation on eroded plots and reclaiming pastures and forests.

In each land unit, the topsoil volume has to be greater than a minimum volume per hectare of crop. If the soil volume falls below the minimum level, a variable representing insufficient soil depth takes on a positive value. This variable has an effect on yields in the production function. An equation is then added limiting each ton of soil deficit to the cropped area. This equation allocates the soil deficit to each crop within the land unit. The model can adopt soil conservation techniques such as terraces, live barriers, grass strips, or fertilization to reduce erosion, but only if these techniques are profitable.

Forest and Perennials

There are three types of trees in the model: pines, coffee in traditional plantations, and coffee in intensive plantations. Each land unit has different initial areas and volumes of pine groves by age group (1–4 years and older) and different wood productivity levels. If a cropland or pasture is abandoned, it returns to forest. Dead wood is collected for domestic consumption. When a plot is cleared to become a field or a pasture, dead wood can be used as fuelwood. Coffee trees are assumed to start producing beans three years after planting. The model can plant two varieties of coffee, a traditional variety and a more productive variety.

The Biophysical Model EPIC

Characteristics of the Model

The biophysical model EPIC is used to describe how land use practices affect yields and soil quality and how land quality in turn affects future crop yields. EPIC simulates hydrology, erosion, sedimentation, phosphorus and nitrogen cycles, plant growth, and soil temperature. The interactions of these simulations are calculated on a daily basis, with the weather for each day generated by a random weather generator. In EPIC, yields are expressed as a fraction of biomass, which in turn is a function of solar active radiation and leaf area. Leaf area is simulated as a function of heat unit accumulation, crop development stage, and crop stress. Stress factors that reduce biomass growth are lack of nitrogen, phosphorus, and water, as well as inadequate temperature, soil compaction, excessive soil acidity, and aluminum toxicity. Soil erosion decreases biomass growth by leaching nutrients and by reducing root growth when roots reach more compact soil layers. Erosion levels were estimated using the Modified Universal Soil Loss Equation (MUSLE) adapted for small microwatersheds (Williams, Jones, and Dyke 1987).

Scientists have applied EPIC to many tropical conditions (Abruna, Rodriquez, and Silva 1982; Pavan, Bingham, and Pratt 1982; Williams, Jones, and Dyke 1984). The argument that EPIC has been developed in the United States and thus is not adapted to tropical conditions is not exact. Many of the components of EPIC have been calibrated with data collected under tropical conditions in the United States and elsewhere. The main criticism that can be made of EPIC is that it has been developed for agriculture based on fertilizers and improved germplasm. The model is less reliable in extensive systems where crop performances depend upon the natural fertility of the soil. In La Lima, the agriculture is intensive enough to be modeled with EPIC.

Results

EPIC was parameterized to the soil conditions, climate, and cropping pattern found in La Lima and the model enacted yields of maize, onion, potatoes, and tomatoes grown in different rotations. Each scenario involved keeping the same climatic sequence, in order to compare different scenarios. Yields used in the linear programming model are the average of the yields obtained from 12 years' simulations with EPIC. Agronomic characteristics of the maize included in EPIC were adjusted to obtain yields similar to local yields. EPIC does not take into account the competition between crops and weeds typical of farming systems where herbicides are not used.

To evaluate the simulated effects of soil erosion on crop yields, erosion and nonerosion scenarios for three different types of slopes and fertilizer practices were compared. The results for maize and potatoes planted in a deep soil (30 centimeters) are reported in Tables 4.1 and 4.2. These simula-

Table 4.1 Simulated effects of soil erosion and fertilizer use on maize yields on three different slopes (tons/ha)

	Slope		
Scenario	**10%**	**22%**	**35%**
Yields with no erosion and no NPK	1.585	1.588	1.601
Yields with erosion and no NPK	1.573	1.536	1.471
Erosion	12.980	59.480	171.000
Yields with no erosion and NPK = 100 kg	2.135	2.134	2.130
Yields with erosion and NPK = 100 kg	2.127	2.103	2.043
Erosion	7.700	34.320	93.590
Yields with no erosion and NPK = 300 kg	2.887	2.874	2.848
Yields with erosion and NPK = 300 kg	2.880	2.864	2.811
Erosion	4.650	14.320	44.900

Note: NPK indicates inorganic fertilizers.

Table 4.2 Simulated effects of soil erosion and fertilizer use on potato yields on three different slopes (tons/ha)

	Slope		
Scenario	**10%**	**22%**	**35%**
Yields with no erosion, NPK = 500 kg	14.364	14.320	14.215
Yields with erosion and NPK = 500 kg	14.060	13.440	13.130
Erosion	39.000	163.000	612.000
Yields with no erosion and NPK = 700 kg	16.446	16.390	16.272
Yields with erosion and NPK = 700 kg	16.215	15.720	15.156
Erosion	28.000	123.000	451.000

Note: NPK indicates inorganic fertilizers.

tions illustrate that the use of fertilizers increases soil cover, which reduces erosion.

The model also simulated scenarios with various soil depths to obtain the long-term effects of soil erosion instead of the short-term effects reported in Tables 4.1 and 4.2. When soil depth becomes insufficient, the yield decline is significant. The results from the EPIC simulations are incorporated into the economic model.

CHAPTER 5

Model Simulation Results

The primary purposes of constructing the model were to discuss induced innovation hypotheses and to explore the consequences of alternative policy scenarios for the La Lima microwatershed. However, before presenting the relevant simulations, we first articulate the baseline results for 1975–95 and how they are validated against the actual history of the La Lima microwatershed over this period.

Baseline Scenario

The baseline scenario compared land use generated by the model with the historical information obtained from farmer interviews in La Lima. The result of this comparison establishes the validity of the model and its ability to replicate correctly the decisions taken by farmers in the community, with particular focus on the evolution of incomes, crop yields, commercialization, land management, erosion trends, water management, and shadow prices.

The historical events known to have had an impact in La lima were introduced progressively into the simulation. These included the diffusion of sprinkler irrigation in 1979; the construction of an all-weather road in 1985; its improvement in 1993; and the construction of a water distribution system in 1992. Changes in historical prices were also fed into the model, because they were determined exogenously (Figure 5.1). Prices had been under strict government control until 1989, but this changed dramatically after the structural adjustment program of 1990, which comprised changing the system of export and import taxes and devaluing the local currency.

Land Use

The simulated land use shows an evolution similar to that recalled by farmers in the plot history survey (Figures 5.2 and 5.3). In both cases, land use changed only slightly despite population growth, which increased steadily from 37 inhabitants per square kilometer in 1975 to 56 inhabitants in 1995. The main change in land use is the progressive development of vegetable production, induced by exogenous events such as the introduction of irrigation sprinklers, the road, market liberalization, and the potable water system.

The uptake of irrigation was slower in the plot history data than in the model simulation. This is because the model does not account for the time needed to learn a new technique. The model is also optimistic about the availability of savings among small farmers.

Figure 5.1 Deflated prices of the main products

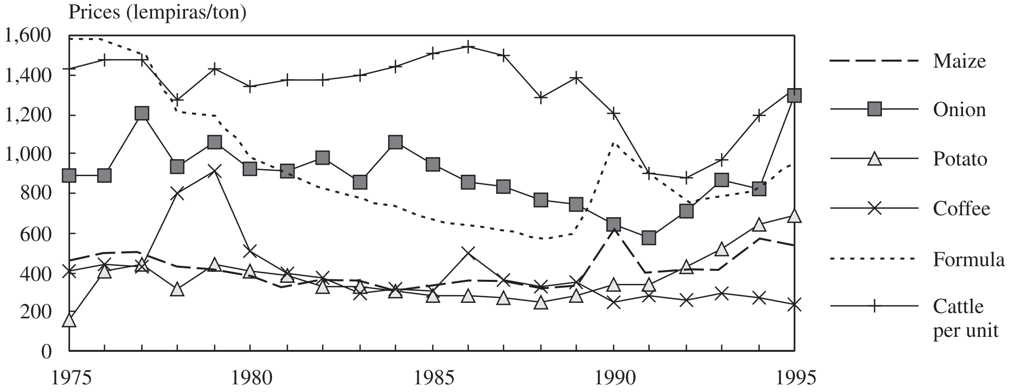


Figure 5.2 Simulated land use

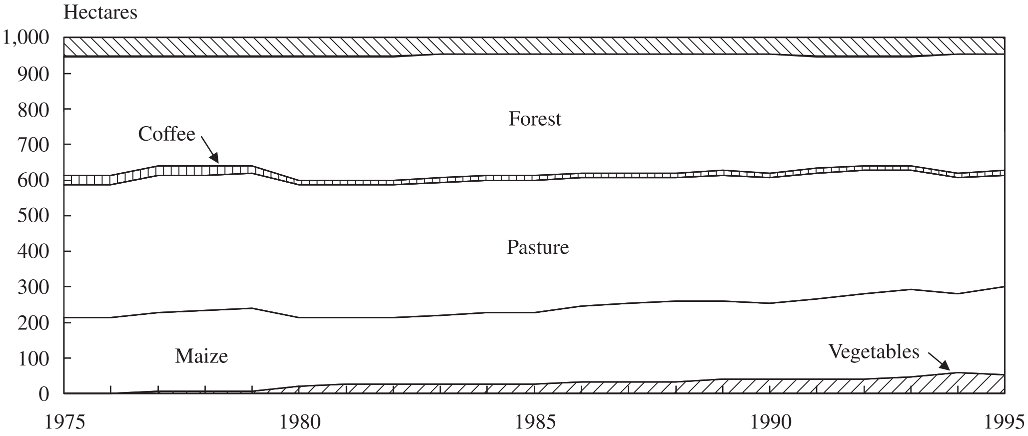
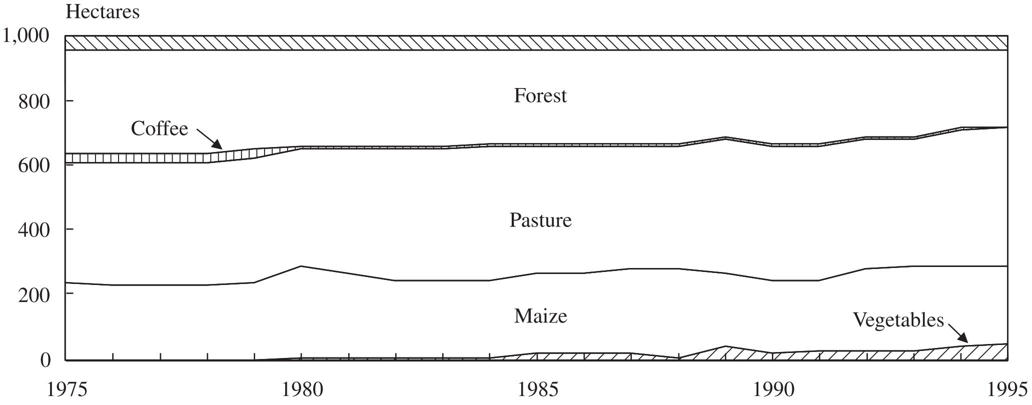


Figure 5.3 Historical land use



Source: Authors' data.

The forest area decreases only slightly over time, both in the model and in reality. This is explained in the model by the considerable amount of labor time necessary to clear the forest. This result suggests that the current forest area is stable and that even removal of the current prohibition on tree cutting might not increase deforestation by farmers. The model does not require trees to be cut for energy needs because dead wood gathered by cleaning the existing forest provides sufficient fuelwood.

The coffee plantation area decreases over time in the simulation as it did in reality. In the model, this occurs because small farmers cut their coffee plantations in favor of vegetables, which offer better economic returns. The profitability of coffee increases slightly when the planning horizon in the model is extended, but not enough to compete with vegetables given the current price conditions in La Lima.

Figure 5.4 shows the simulated land use by slope category. Soils with less than 15 percent slopes are predominantly in pastures. This is because water-logging on flatter fields results in lower yields than on soils with a steeper slope. The 15–30 percent slope area is covered mainly with crops and pastures, while the forest area decreases over time. The 30 percent sloped land has the more extensive forested area and, surprisingly, includes a significant area of cropped land.

Figure 5.5 shows the simulated land use for three different zones of the microwatershed. The upper zone has the largest proportion of crops and pastures while the two lower zones still have extensive forests.

Figure 5.6 shows the simulated land use for each group of farmers. Small farmers

Figure 5.4 Simulated land use by slope (o_1 = flat, o_2 = medium, o_3 = steep)

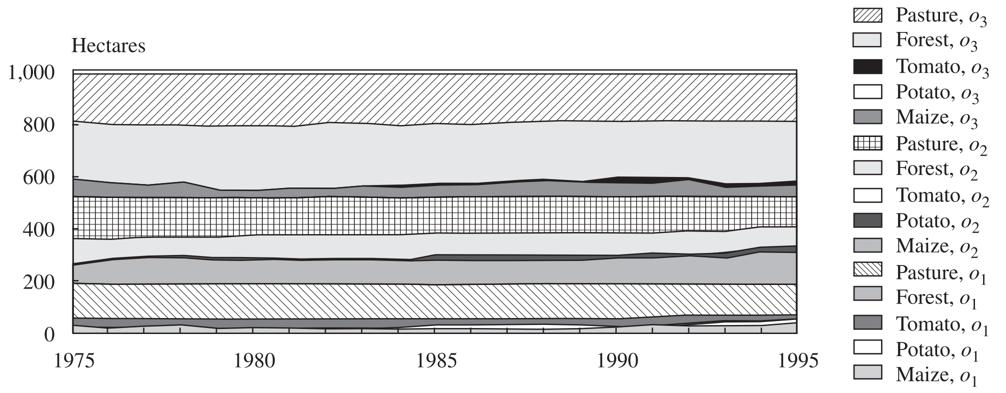


Figure 5.5 Simulated land use by zone (s_1 = top, s_2 = medium, s_3 = lowest)

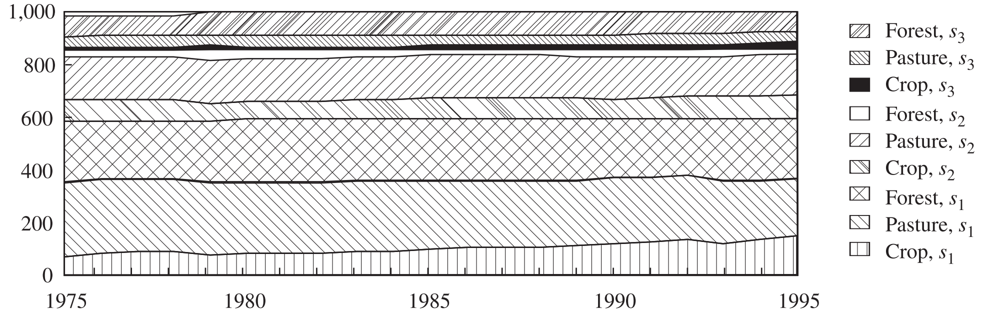


Figure 5.6 Simulated land use by type of farm (h_1 = ranchers, h_2 = small farmers)

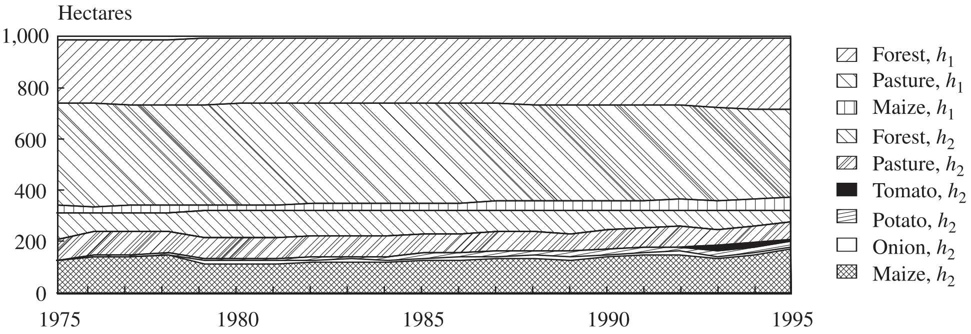
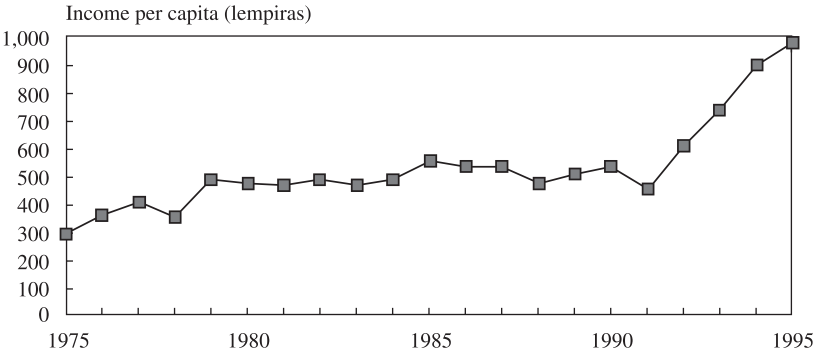


Figure 5.7 Simulated income per person



have more than half of their holding under crops with a decreasing area of forest over time, whereas ranchers have mainly pastures and forest.

Incomes

There are two distinct periods in the evolution of per capita income: first, a period of slow increase before the market liberalization policies of 1990; and, second, a period of dramatic increase after market liberalization (Figure 5.7).[11] The increase during the first period is due to technological improvements, which allow incomes to rise slightly despite worsening prices and continued population growth. After 1990, however, simulated real income doubles in less than four years because of rapidly increasing vegetable prices.

There were sizable differences in the results for different types of farmers (Figure 5.8). Ranchers' per capita income decreases continuously after 1985 as meat prices declined. Small farmers' income increases slightly in that same period due to exogenously introduced varietal improvements. After market liberalization, all incomes increase at a similar pace because meat and crop prices increase.

Income sources also change over time (Figure 5.9).[12] Incomes from livestock decrease, while onions and potatoes replace

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[11] All costs and incomes are deflated to 1987 prices with the Consumer Price Index (World Bank 1997) and are in lempiras (in 1987, one lempira was equal to US$0.30).

[12] In all graphs that report incomes, the value of leisure is included in income. The value of leisure is small and changes only slightly in the different scenarios.

Figure 5.8 Simulated income per person by farmer group and zone (s_1 = top, s_2 = medium, s_3 = lowest)

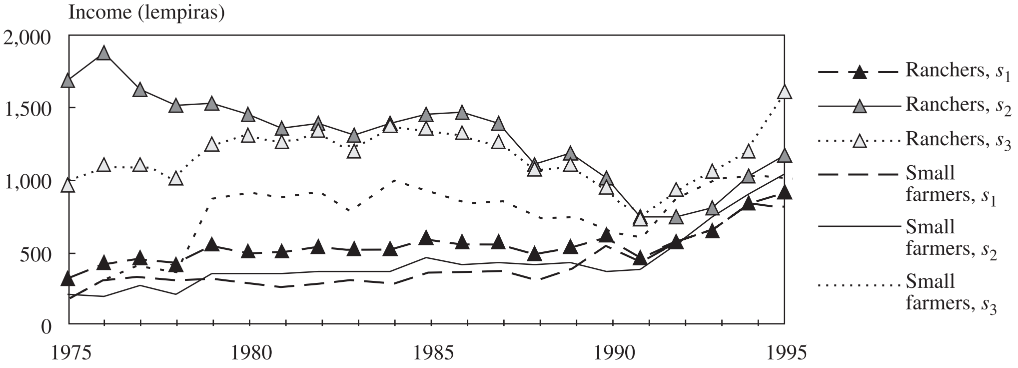
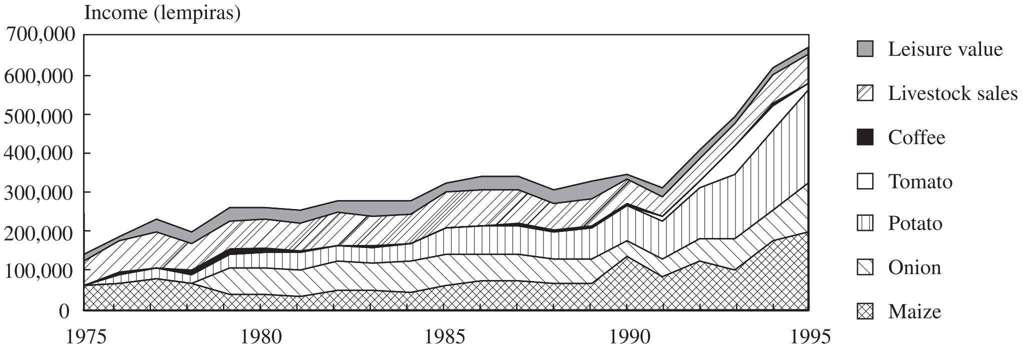


Figure 5.9 Simulated sources of income in the whole microwatershed



maize as the primary source of income. Coffee and off-farm activities remained marginal sources of income.

Crop Production

The simulated yields of maize, onions, potatoes, and tomatoes increase steadily through time thanks to technological improvements in the form of improved varieties (Figure 5.10) and increasing application of fertilizers (Figures 5.11 and 5.12).[13]

The simulated yields for 1995 are close to the actual yields farmers obtained in La Lima. Surprisingly, however, the recent crop price increases do not result in large yield increases. This is explained in the model by the limited availability of labor at harvest time.[14] The model prefers corralling (where cattle graze maize residues) to compost or manure production because of the latters' high labor requirements.

Commercialization

The sale of part of production increases with time, particularly after the adoption of irrigation and fertilization techniques in 1979–80, and after the construction of the road in 1985 and its improvement in 1993 (Figure 5.13). When irrigation is adopted in 1979, the model begins selling less maize

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[13] The quantity of inorganic fertilizer per hectare increases in steps because of the linearity of the solver. In reality, fertilizer use increases more continuously.

[14] Note that the model did not allow for immigration, because it does not occur in reality, as neighboring communities also have a labor shortage. Note also that families provide most of the labor and that wage labor remains relatively marginal.

Figure 5.10 Simulated yields

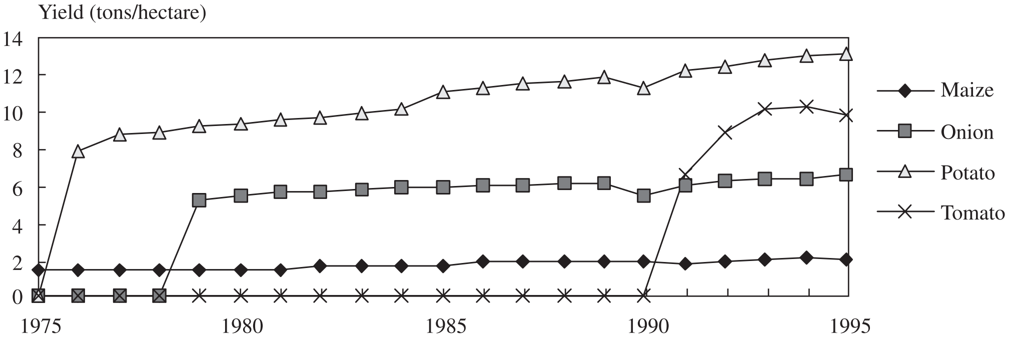


Figure 5.11 Simulated fertilizer use

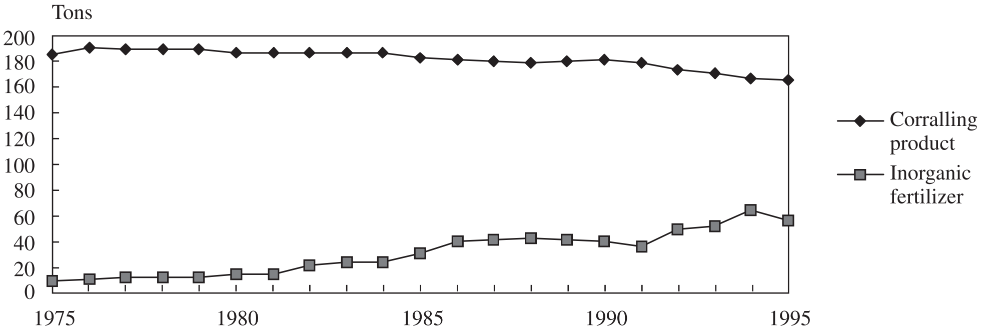


Figure 5.12 Simulated inorganic fertilizer use per hectare

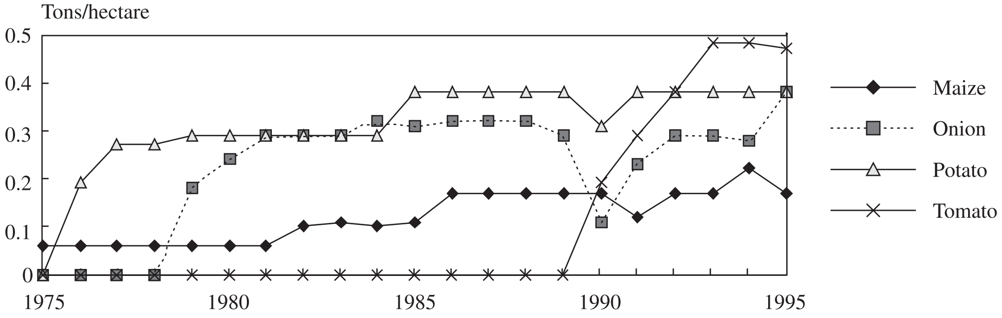
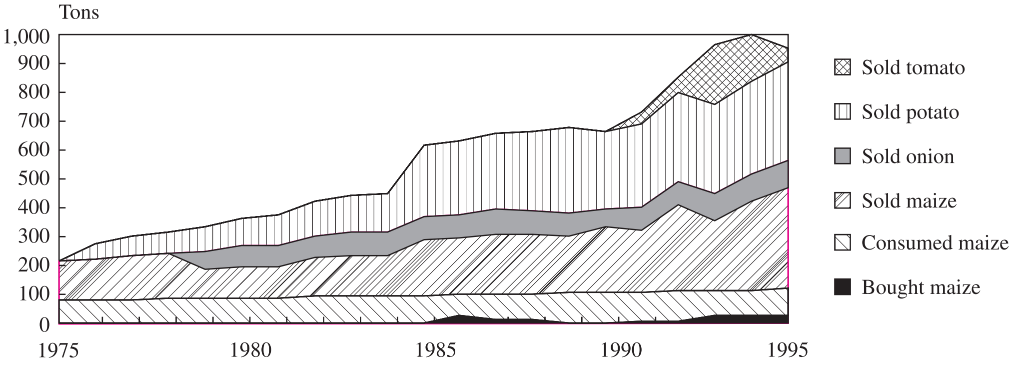


Figure 5.13 Simulated use of crop production



and more onions and potatoes. When the road is constructed in 1985, the model sells even more potatoes, and starts to buy a portion of the maize that is consumed locally. When the road is improved in 1993, the model diversifies into fresh vegetables such as tomatoes. Surprisingly, however, maize remains a competitive crop all along. The reasons for this will be explored later.

Ranching

Improved prices for vegetables and maize create an incentive to convert pasture into cropland. Accordingly, the model slowly decreases the cattle herd throughout the simulation (Figure 5.14). Despite the low return per unit of land, however, ranching remains in the solution because ranching requires limited labor, and fencing can be done during periods of low activity.

The model increases the small farmers' cattle herd in 1979 because the introduction of irrigation and the increasing intensification of farming reduced the total need for cropland and freed it up for conversion to pastures. Ranchers do not increase their herd, however, because all their pastures are used and the conversion of existing forest into pastures is labor consuming.

Mule numbers decrease over time because the new road makes local transportation less necessary (Figure 5.15). The volume transported by mules decreases twice: first in 1985 when the road is built, and then again in 1993, when the road is improved. Oxen numbers increase only in the upper zone of the microwatershed where the cropped area also increases the most.

Erosion

The average simulated amount of soil erosion for the whole microwatershed is close to 6,700 tons per year (or 7 tons per hectare per year) (Figure 5.16). This is almost the same amount as was estimated in 1996 at the outstream of the microwatershed.[15] To obtain this result, however, the nutrient effect of erosion on yields had to be suppressed. If the nutrient runoff effect is maintained, then the simulated erosion becomes less than 3 tons per hectare because the model adopts grass strips on 40 hectares at the beginning of the simulation. This technique was adopted by the model because it reduced erosion while requiring little labor and investment, its only cost being the space occupied in the field. The model compensated for this lost area by expanding the cropland area—the population density being low enough in La Lima to make such an expansion affordable.

In reality, farmers did not adopt grass strips. According to our interviews, farmers were not aware of the effects of erosion on yields. Simulations with EPIC also suggest that the effects of erosion on yields are small where soils are deep enough (less than 3 percent yield loss per year on steep slopes). Moreover, incomes increase by only 1.2 percent in the model after removing the nutrient effect of erosion, again showing a small effect. In other words, the model reacts to something that farmers do not think is important. Consequently, removing the nutrient effect of erosion in the baseline scenario mimicked farmers' perceptions. However, the results in this report maintain the erosion calculation and the soil depth effect on yields.

In the baseline scenario, soil depth diminishes rapidly on the steeper slopes (Figure 5.17) and quickly reaches the level where roots become affected. The model reacts by abandoning these plots and reclaiming new ones, given this approach is less expensive than the construction of soil conservation infrastructures. A notable exception to this pattern arises in 1991 in the most populated land unit, which also has a high proportion of steep slopes. In this case, the model invests in the development of terraces on 10 hectares (Figure 5.18). The model does this as the critical soil depth becomes

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[15] The two quantities differ slightly because the total sedimentation at the out-stream is not the sum of erosion at the plot level. A stream can deposit part of its sediment before it reaches the out-stream of the microwatershed; conversely, the stream can carry to the outlet sediments captured in the channel of the stream itself.

Figure 5.14 Simulated livestock herd size

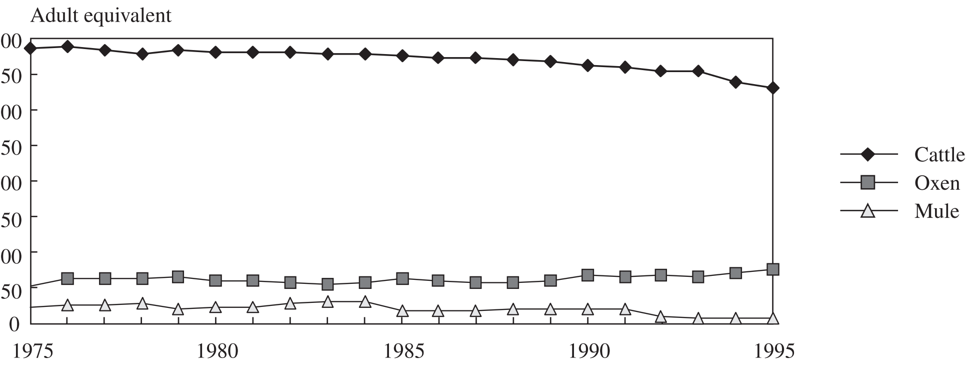


Figure 5.15 Simulated transportation by mule

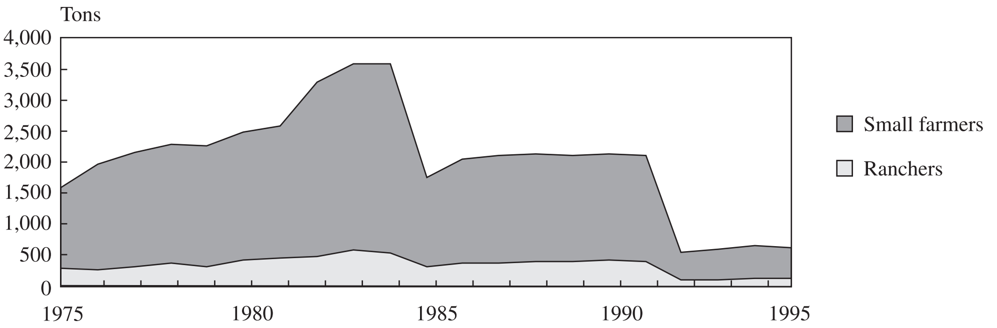


Figure 5.16 Simulated erosion aggregated by slope

Figure 5.17 Simulated soil depth in three land units

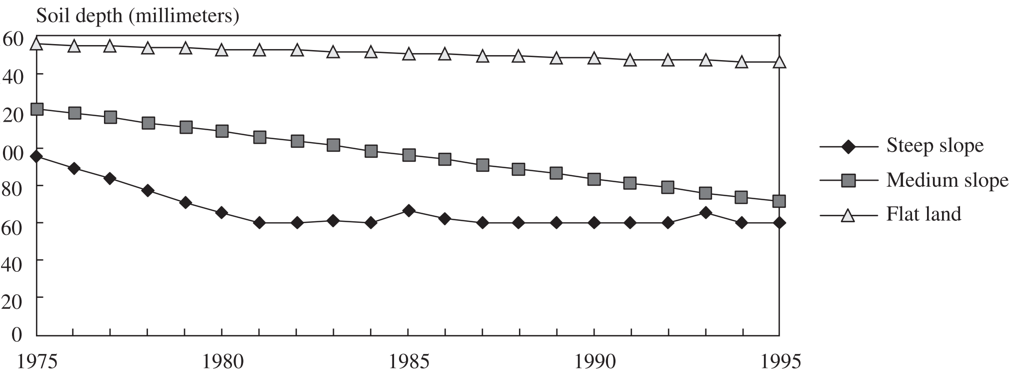
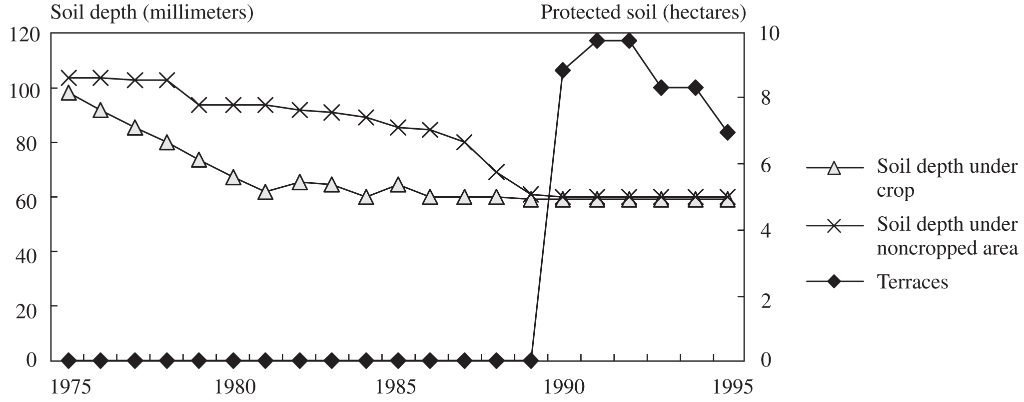


Figure 5.18 Simulated soil depth and soil conservation structure in one land unit



insufficient, and there are no more pastures or forest lands available for cropping. These results correspond to reality, and today this land unit is the one with the most conservation structures.

Water Management

The model replicated quite accurately the actual use of water, showing a progressive increase from 1979 onward in the use of water for irrigation and human consumption (Figure 5.19). As a result of the introduction of sprinklers into the model in 1979, water outflows from the microwatershed decreased significantly. Figure 5.19 shows that in the upper microwatershed the small amount of spring water is rapidly used for irrigation. After potable water distribution was introduced in 1993, the model used even more water because the distribution system allowed the irrigable area to be extended.[16]

Shadow Prices

The shadow price of a factor of production (land, water, labor, or capital) measures the amount by which the utility function would increase if one more unit of this factor became available.[17] Induced innovation theory suggests that, if population increases, then the shadow price of labor should decrease (holding everything else constant) while the shadow price for land should increase, because land becomes scarce relative to labor. However, in our results, the shadow price of land stagnates while the shadow price of labor increases continuously (Figure 5.20). This result is due to the increasing profitability of labor-intensive activities such as vegetable production. Consequently, farmers have fewer reasons to acquire new land. Land is still abundant in La Lima and extra land would increase current incomes by a small amount. Most small farmers have share-cropping arrangements with larger farmers to produce maize and vegetables on larger farmers' land. These results imply that, for situations similar to those in La Lima, agricultural research and extension should focus on ways to increase labor productivity, particularly during peak periods. For example, labor-saving methods for harvesting maize and vegetables would increase productivity and incomes. Conversely, techniques that increase yields would have a smaller effect on per capita incomes.

The shadow prices of labor vary by period, and are not uniform through time or

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[16] A lower bound was added in the model for the stream volume, because in reality there is an implicit rule that users cannot completely drain a stream.

[17] The shadow price of a factor is the amount by which global net income will increase if one unit of this factor is added. If the factor is not limiting, the shadow price is equal to zero.

Figure 5.19 Simulated water volume in the outflow of the streams by zone

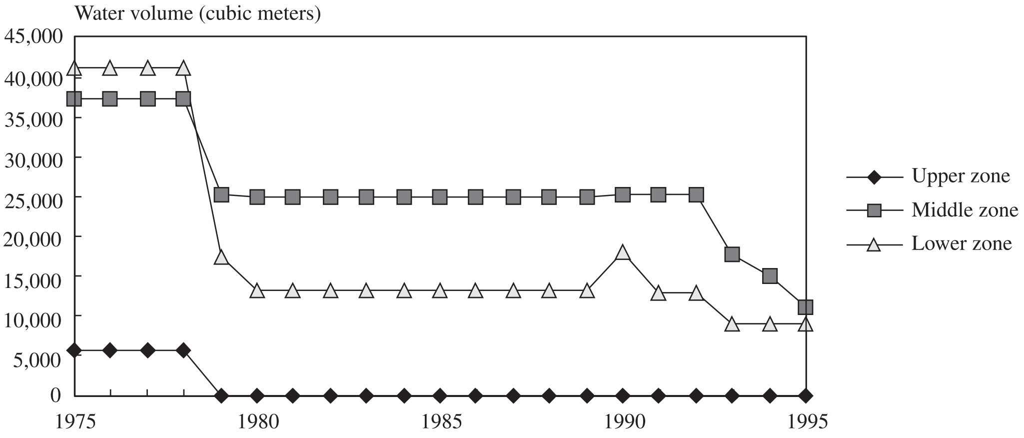


Figure 5.20 Shadow prices of land and labor

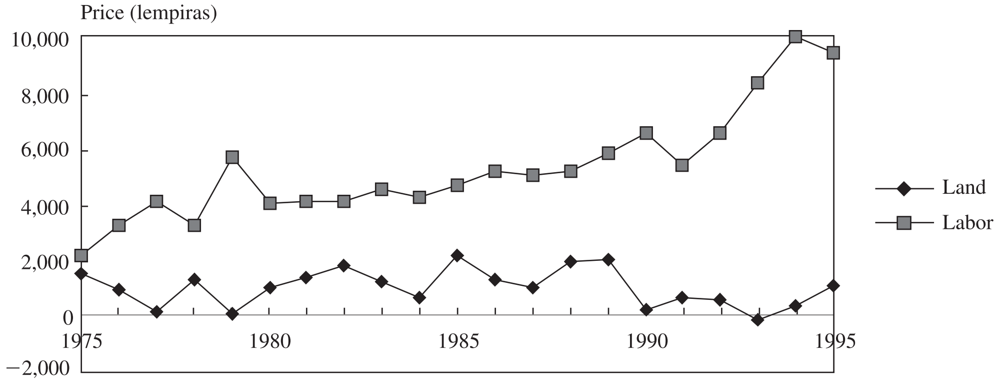
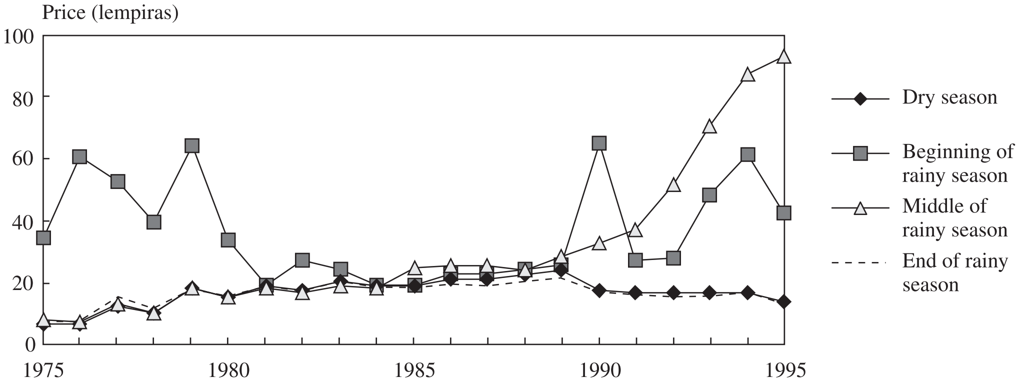


Figure 5.21 Simulated shadow prices of labor by season



season (Figure 5.21). From 1975 to 1981, for instance, the shadow price of labor is highest for the period of land preparation for maize. This means that maize production in that season is most constrained by labor scarcities. Between 1981 and 1989, by contrast, all four working seasons have the same shadow prices, implying that all periods are equally limiting because the model smoothes labor requirements over time by scheduling some tasks during low activity periods. For example, the transportation of maize or inputs can be postponed or planned in advance. Similarly, the *dobla* technique[18] for maize postpones the harvest until more labor is available. After the market liberalization program of 1990, the shadow price of labor by period diverges again (Figure 5.21). The limiting period becomes the middle of the rainy season, when the maize harvest competes with vegetable harvesting and potato planting. Methods to reduce labor requirements during this period would have a big impact on production.

The shadow price of the marketing constraint on vegetables is positive only at the beginning of the simulation and disappears once the road is built (Figure 5.22). At the beginning of the simulation, the marketing constraint depresses the shadow price of labor by limiting vegetable production.

The shadow price of water increases rapidly in the last few years of the simulation because water becomes a scarce resource when the installation of the water distribution system allows an increase in irrigation (Figure 5.23). Water then becomes a binding constraint on expansion of the irrigated area, but the model reacts by producing vegetables during the rainy season.

Hypotheses

In this section, model simulations over the period 1975–95 aid discussion of the induced innovation hypotheses formulated in Chapter 1 about the effects of population pressure, increased market access, and improved technologies and market prices, and the impact of agroecological conditions on these relationships.

The Effect of Population Pressure

The first two hypotheses in Chapter 1 state that increases in population pressure lead to (a) lower per capita incomes and (b) continuing degradation, until some critical value of productivity is reached at which point it becomes profitable to invest in resource improvement. Two contrasting scenarios help in the discussion of these hypotheses: one with increased population pressure, and one in which no population growth is assumed.

To simulate increased population pressure, we allowed permanent workers to migrate into the village but at an annual rate that cannot exceed the annual population growth of the existing farm population. The model will take in new families if the discounted value of their contributions to the community's aggregate utility is at least as great as their costs (additional food requirements, for example). We do not consider the opportunity cost of migrant families outside the community. This is because we are not trying to model migration decisions per se, but only to simulate what will happen in La Lima if the population density were increased.

Since labor is initially scarce in the community and additional family workers prove cheaper than hiring in day labor from outside the community, the model allows in all the additional permanent workers that the constraints permit until a population density of 150 inhabitants per square kilometer is achieved, which is about three times the current density. Beyond this density, total aggregate income starts to decline, and some farmers out-migrate. Per capita income declines to 24 percent of its value in the baseline scenario by 1995 (Figure 5.24). All the forest is cut and households have to turn to

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[18] The *dobla* is a traditional technique whereby the maize stem is bent over right under the cob, which allows the grain to dry in the field and removes the urgency of harvesting.

Figure 5.22 Shadow price of the marketing constraint

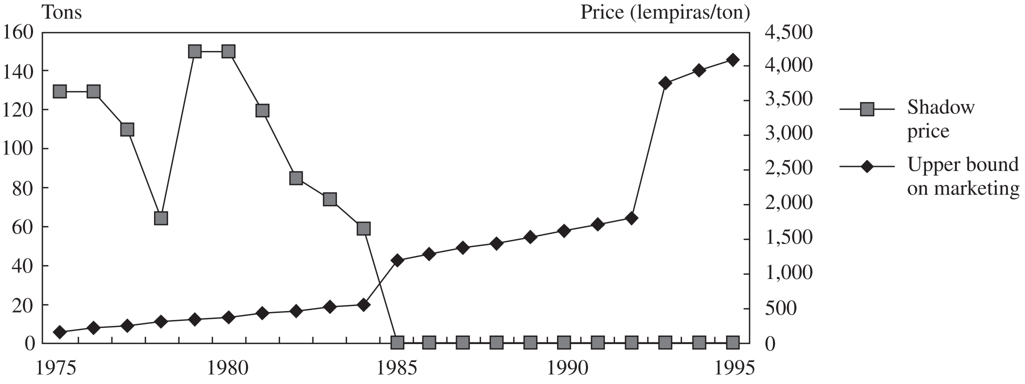


Figure 5.23 Shadow price of water by zone

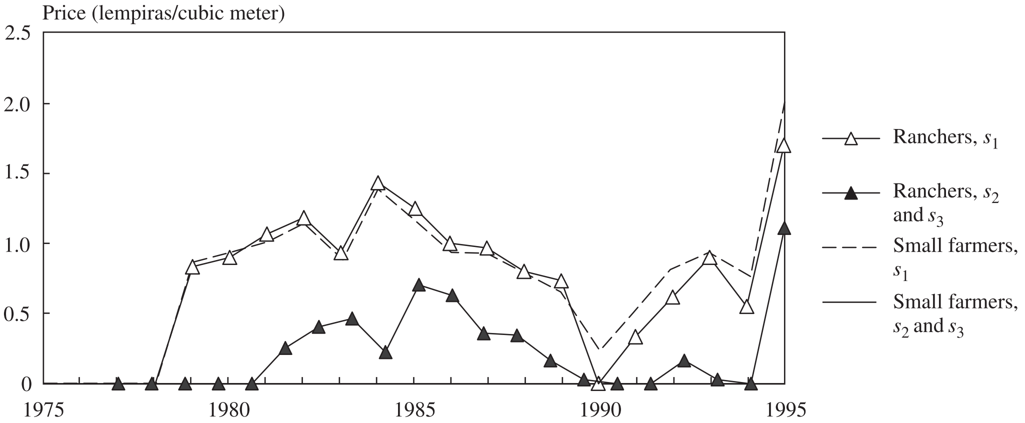
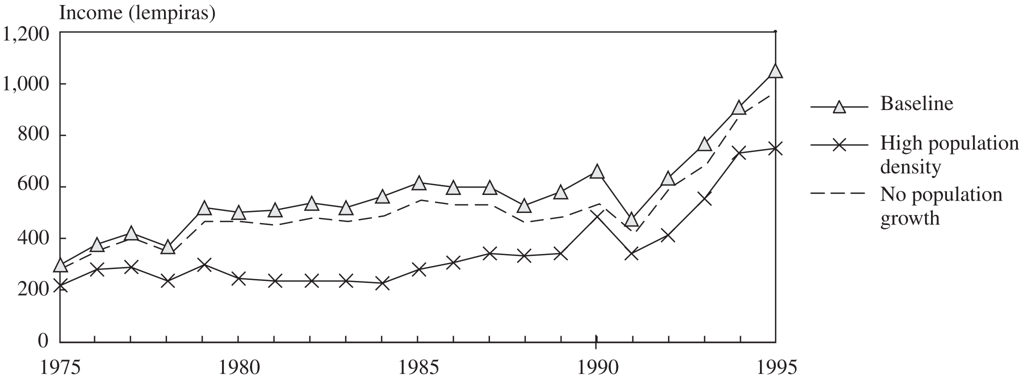


Figure 5.24 Simulated per capita income: Alternative scenarios for population growth



alternative energy sources (for example, kerosene for cooking). Most cattle are also sold, and only a few oxen and mules are kept for productive purposes. Almost the entire microwatershed is cultivated with maize, with a limited area being kept under vegetables. Soil erosion initially rises to more than 25 tons per hectare because steep slopes are cultivated, but then conservation techniques are adopted and erosion declines again by 1994 (Figure 5.25).

When the population is assumed to remain constant at its 1975 level, then per capita income is about 10 percent higher than in the baseline scenario (Figure 5.24). Soil erosion is halved (Figure 5.25).

The results of the two population simulations are similar to our initial hypothesis that, when population density is still relatively low, population pressure has negative effects on natural resources. However, when the population reaches a higher density and the productivity of the resource base is threatened, farmers start to improve their natural resource management practices. This process can be represented by a U-shaped function where the productivity of natural resources decreases to a point where farmers start to invest in their enhancement.

The results also suggest that, with additional population pressure, farmers are likely to expand their cropland by converting pasture rather than forest areas, both because of the low profitability of ranching and because it would be costlier in labor terms to convert forest rather than pasture into cropland. Thus, any future expansion of crops will occur at the expense of pastures, and the forest area will remain largely intact.

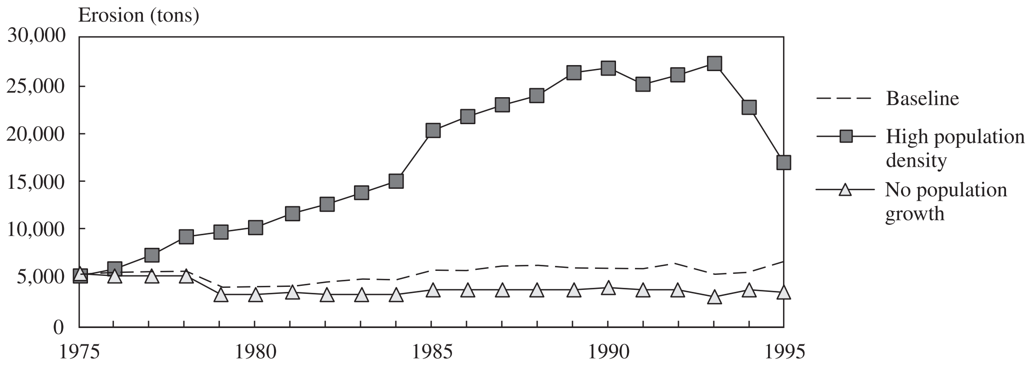
The simulations show too that increased population pressure results in lower per capita incomes, unless technological innovations or higher prices compensate for the decreasing returns to labor. Population growth leads to lower returns per capita because, although every additional worker increases the global income of the community, the income of this marginal worker is lower than the average. This occurs despite the adoption of more labor-intensive activities. Out-migration could theoretically offset these income declines, but outside opportunities are not attractive enough to encourage out-migration in the model.

The Effect of Access to Markets

The hypothesis is that market access increases per capita incomes and promotes land conservation because increases in land value make investments in land improvements more profitable. To simulate this hypothesis, two scenarios simulated the effect of market access, using distance to a road as an indicator of market access.

In the first simulation, the equations capturing the effect of the construction and subsequent improvement of the road in the community are removed. The model responds by transporting products to the next community 6 kilometers away. However,

Figure 5.25 Simulated erosion: Alternative scenarios for population growth



some of the more perishable crops (such as tomatoes) are no longer produced because they cannot be transported this way. The "removal" of the road reduces income by only 11 percent, which is surprising given the importance usually attached to market access (Figure 5.26). The model still produces similar amounts of maize, onions, and potatoes to those in the baseline scenario, and compensates for the lack of a good road by delaying the transport of maize and some vegetables to less busy periods.

Figure 5.27 shows that the road construction leads to a sharp increase in soil erosion; this is because farmers start to produce more potatoes for the market, which are a highly eroding crop.

The model simulated different scenarios with respect to the distance of the microwatershed from the main road—specifically, distances of 20, 30, and 40 kilometers from the village to the main road—plus a scenario in which the distance remains unchanged but the connecting road is removed. All transportation must be made by mule. This simulated situation of remote market access (which is actually quite typical of the Central Region) has a radical effect on per capita incomes (Figure 5.26). Coffee production increases sharply in the simulation after the coffee price boom of 1979, whereas the maize area declines to the minimum area needed to meet local food consumption. Maize is not intensified and yields remain low because the model does not find sufficient labor to transport fertilizers. Surprisingly, the model produces potatoes and irrigated onions and transports them to market by mule. The number of cattle increases to reach 30 percent more units than in the baseline scenario; this is explained by the decrease in maize area. However, cattle

Figure 5.26 Simulated per capita income: Alternative scenarios for access to markets

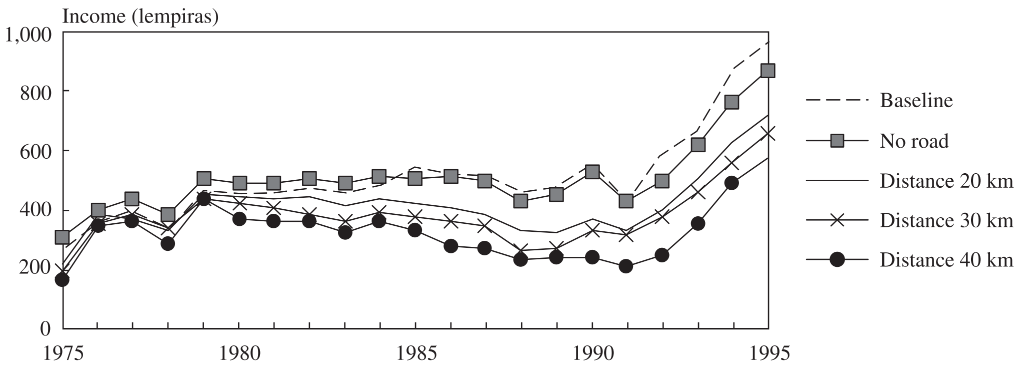
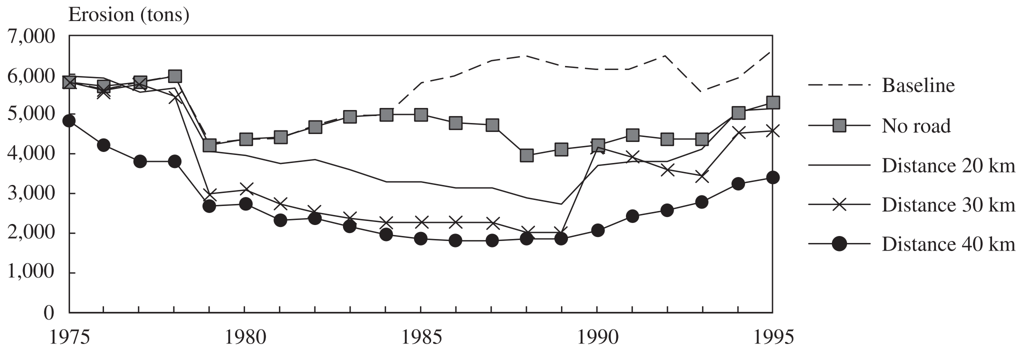


Figure 5.27 Simulated erosion: Alternative scenarios for access to markets



numbers decrease again after the liberalization when farmers allocate more labor to vegetables.

Soil erosion decreases when the distance to the road increases because the cropped area becomes smaller (Figure 5.27). Land conservation infrastructures are still not adopted, as soil depth never reaches the critical levels where yields are reduced. Erosion increases after the liberalization because farmers plant more rainy season vegetables.

These simulations underline the role of roads in determining the development pathway that a community may follow. Coffee is more profitable than maize in remote areas. Onions and potatoes are also profitable even if the produce has to be transported by mule to the closest road. The simulations suggest that erosion decreases with the distance to roads because the cropped area decreases as more time is spent in transport. The initial hypothesis held the expectation that better road access would mean more investment in land conservation structures. This does not happen because the model finds it more cost-effective to allocate labor to production than to invest in terraces or live barriers.

The Effect of Technological Improvement

The fourth hypothesis states that technological innovation compensates for decreasing returns to labor. To simulate this hypothesis, the model simulated removal of three technologies from La Lima, namely crop variety improvement, sprinkler irrigation, and the potable water distribution system.

Crop Variety Improvement. Per capita incomes fall dramatically after we remove the new crop varieties (this was done by keeping the same crop response to fertilizers as in 1975): in 1995, per capita incomes are 41 percent lower than in the baseline scenario (Figure 5.28). Incomes decrease until 1989, but then begin to increase again after the market liberalization. Despite population pressure and higher commodity prices, yields and the amount of fertilizer used per hectare remain almost the same. The 1995 maize area is 6 percent larger than that in the base scenario because the model uses more extensive production methods with less labor per unit of land. Erosion remains low without technology improvement, because the potato area is much smaller than in the baseline scenario (Figure 5.29).

Irrigation in 1979. Sprinklers were introduced by the extension services in 1979. If this technology is eliminated, the model simply stops producing vegetables during the dry season. However, the model compensates for the loss of income by producing more maize and vegetables during the rainy season and transporting maize and some vegetables to the markets during the then less busy dry season (Figure 5.28).

Figure 5.28 Simulated per capita income: Alternative scenarios for technologies

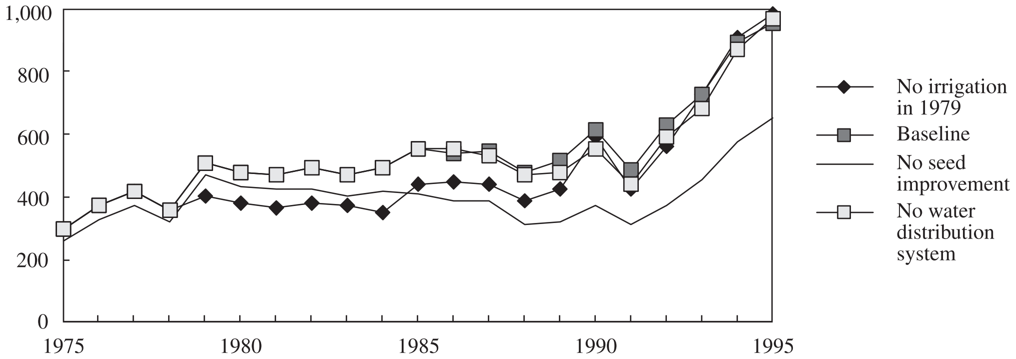
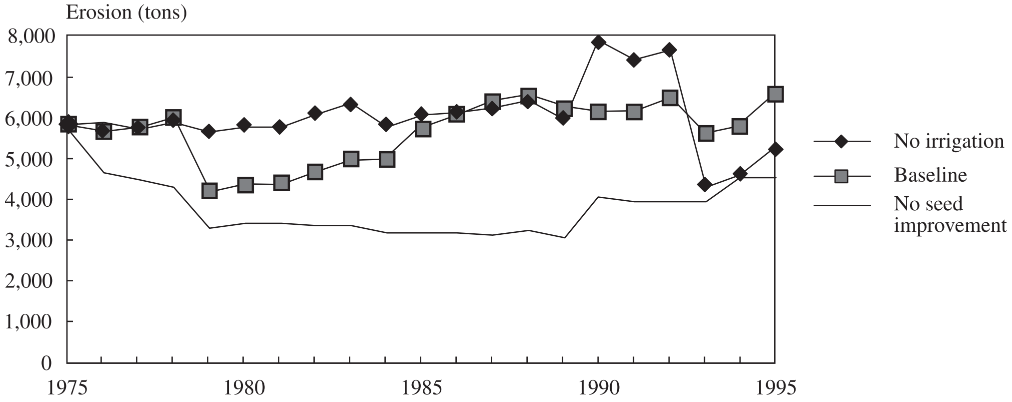


Figure 5.29 Simulated erosion: Alternative scenarios for technologies



Erosion is slightly greater without irrigation than with irrigation, leading to soil depth problems and a return to pastures, which in turn results in lesser erosion in 1995 (Figure 5.29). This last result underlines the importance of dynamics in natural resource management. A community may have a current low level of erosion because farmers previously eroded their plots so much that finally they reached a critical soil depth and had to invest in conservation structures. Or a community may currently have more erosion compared with another community because farmers still have deep soils thanks to better soil management.

Potable Water Distribution in 1993. Simulating removal of the potable water distribution system in 1993 results in a slightly lower income increase of about 2.5 percent (Figure 5.28). The water distribution system has a smaller than expected impact on incomes, because it was not designed for irrigation. In reality, however, the potable water distribution system has a larger impact on equity because it allows almost every farmer to produce at least a few square meters of vegetables near the house during the dry season, whereas, before, only farmers with plots near the main streams could produce vegetables. The potable water distribution system has no effect on erosion.

Conclusions. Seed improvement had a significant impact on per capita incomes through its effects on vegetable and maize production. In fact, it more than offset the negative impact of population growth on per capita income, thereby affirming our hypothesis. In reality, however, poor farmers in La Lima used inferior varieties of seeds. This suggests that credit and extension programs would likely have an important effect on production and incomes, as well as on the distribution of income.[19]

The adoption of sprinkler irrigation was also an important source of technological change in La Lima. However, irrigation had a smaller than expected impact on yields because the dry season is short and vegetables can be produced during the rainy season. The use of a gravity-fed system makes irrigation possible anywhere below water collection points. In practice, however, irrigation in La Lima is concentrated in areas closest to streams and water points. The

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[19] Extension services are often considered to be ineffective. It is true that extension services have limited success when they promote land conservation practices. In La Lima, however, farmers were relatively positive about extentionists' impact, explaining that extension services brought the new seeds and the sprinklers currently used in the area. In the hillsides of Honduras there is little adoption of new technologies without the help of extension services (Bunch and López 1995).

introduction of the potable water distribution system did not markedly increase the production of vegetables, but it did enable the benefits of irrigation to be spread more equitably across farmers.

Seed improvement worsened erosion because it increased rainy season potato cultivation. The adoption of sprinklers first reduced erosion by reducing the area of rainy season crops, but irrigation, by increasing the labor cost during the dry season, makes investment in land conservation less likely.

The Effect of Agroecological Conditions

The hypothesis is that agroecological conditions are the most important factor determining incomes and resource conditions. Three simulations were run to discuss this hypothesis. The first assumes that vegetables can no longer be produced during the rainy season, a situation that is common in many of the lower-altitude areas of Central Honduras because of unreliable rains. The second assumes that vegetable production is not possible at all, again a common feature in many less-favored hillside areas. The third simulation assumes shallower soils.

No Rainy-Season Vegetables. Confronted with the absence of a reliable rainy season, the model increases the production of maize and grows a few hectares of irrigated onion during the dry season. Per capita income is 39 percent lower in 1995 than in the baseline scenario (Figure 5.30). The maize area is greater than in the baseline scenario and also has higher yields, because more labor can be devoted to maize production. Despite the greater area of maize, less erosion occurs because rainy season vegetables are the main cause of erosion (Figure 5.31).

No Vegetables. If vegetables cannot be produced at all in the microwatershed, income would fall to 30 percent below the baseline in 1995 (Figure 5.30). The model attempts to compensate for income losses by producing more maize. This leads to some decline in soil erosion, particularly after the road is constructed in 1985 (Figure 5.31).

Reduced Soil Depth. Given shallower soils, the model has farmers invest earlier in land conservation techniques (terraces, live barriers, and grass strips), with the result that soil erosion is rapidly reduced to less than 2 tons per hectare (Figure 5.31). The labor spent in constructing land conservation structures initially reduces per capita incomes, but incomes return to baseline levels once the construction work is completed (Figure 5.30).

This important simulation shows that policies to reduce erosion are more likely to succeed in areas where soils are shallow. In regions with deep soils, farmers are likely to be much less responsive to land conservation programs.

Figure 5.30 Simulated per capita income: Alternative scenarios for natural resource constraints

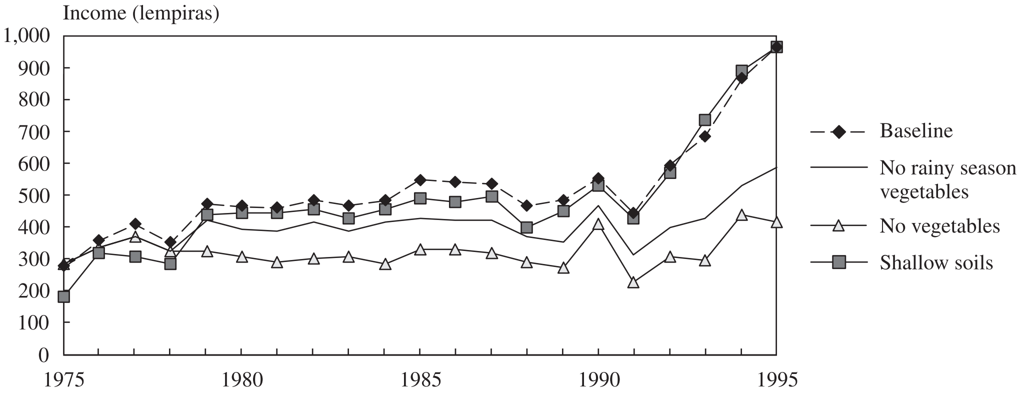
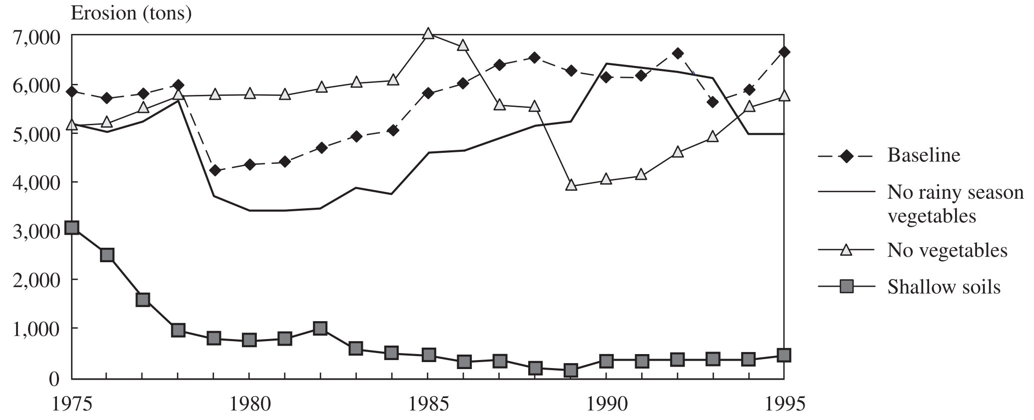


Figure 5.31 Simulated erosion: Alternative scenarios for natural resource constraints



Conclusion about Agroecological Conditions. The first two simulations show that climate is a major factor in explaining income differences across communities. If vegetable production is impossible, per capita incomes are much lower. The simulation for reduced soil depth suggests that soil depth has a small impact on income because land conservation structures are not very costly. However, if these conservation structures are not built, incomes decrease to very low levels.

Policy Interventions

The bioeconomic model provides a tool for simulating the possible impact of alternative policy interventions on incomes and natural resource conditions. The policy scenarios simulated below were selected because of their relevance to ongoing policy discussions in Honduras. Each case simulated what the impact would have been during the period 1975–95. First, what would have happened if the liberalization of 1990 had not occurred? Second, what would progress have been without the use of inorganic fertilizers? Then a land reform simulation forecast how this would have affected the development of the community. The final scenario shows whether dairy markets would have developed in La Lima if there had been access to a processing plant.

Market Liberalization

This study examines the impact of market liberalization by "canceling" this policy in 1990 and keeping prices at their 1990 level thereafter.[20] In the first three years after 1990, the scenario without liberalization produces higher incomes because prices were more favorable to vegetable production. However, by 1995, incomes without liberalization are 32 percent lower compared with the baseline scenario (Figure 5.32), showing that, in the longer term, liberalization did increase incomes. Another positive effect of liberalization is that it reduced income inequality, as the increased profitability of vegetables diverted labor from wage work on ranches to vegetable production. The liberalization led to higher fertilizer use, which increased yields, and increased labor demand per hectare. This extra labor requirement per unit of land reduced the area planted and hence improved soil erosion slightly (Figure 5.33).

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[20] It is not possible to assert what prices would have been after 1990 without market liberalization, but it appears plausible to assume that the direction of price changes since 1990 is consistent with what one would expect the market liberalization and its devaluation policies to have caused.

Figure 5.32 Simulated per capita income: Scenario without market liberalization

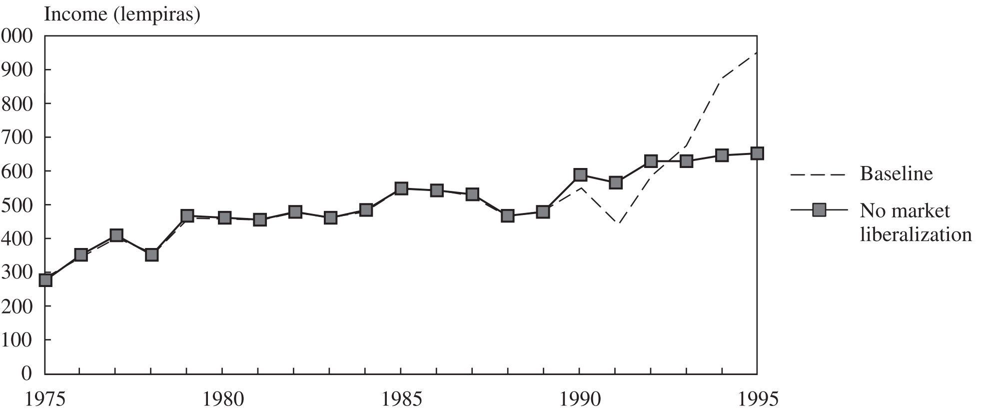
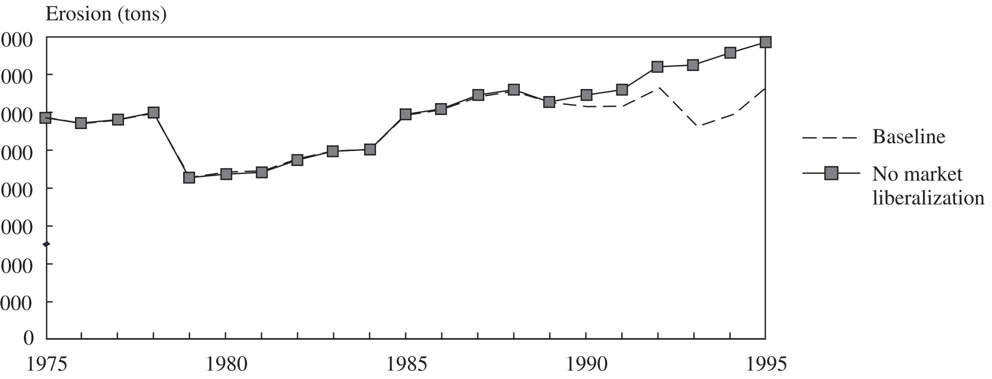


Figure 5.33 Simulated erosion: Scenario without market liberalization



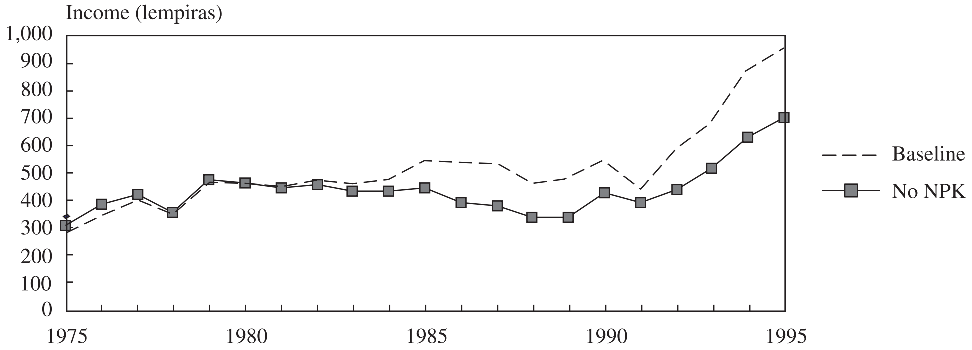
No Inorganic Fertilizer

This scenario simulates what would have happened during 1975–95 without the use of inorganic fertilizers. There are regular discussions in Honduras about using inorganic fertilizers because of the environmental contamination and economic dependency that imported non-organic inputs create. According to the model, a ban on inorganic fertilizers would have reduced net per capita income by 29 percent by 1995, compared with the baseline scenario (Figure 5.34). To compensate for the lost nutrients, the model produces up to 850 tons of compost per year while continuing to corral cattle. However, lower maize yields lead to less crop residue, which in turn reduces livestock feed and livestock manure. The model also brings more land under cultivation to compensate for losses in yields. Furthermore, lower fertilization decreases soil cover by crops. These changes lead to a 35 percent increase in soil erosion by 1995 compared with the baseline scenario (Figure 5.35).

Land Redistribution

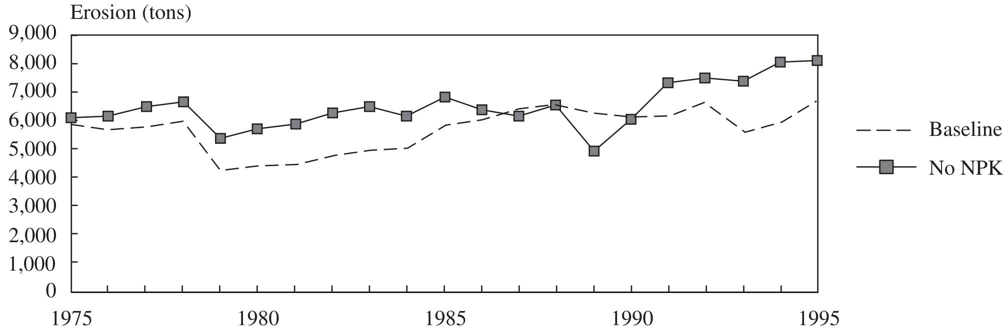
In this scenario, the model allows the population to move freely within the microwatershed, and spatially relocates farmers so as to maximize total and average community income, as would happen with a well-conceived land reform. This contrasts with a baseline scenario in which farmers are constrained by the initial land endowments within each submodel, and no land transactions (either sale or lease) are allowed between submodels. Under this new scenario, the model suggests moving some of the

Figure 5.34 Simulated per capita income: Scenario without inorganic fertilizer



Note: NPK indicates inorganic fertilizers.

Figure 5.35 Simulated erosion: Scenario without inorganic fertilizer



Note: NPK indicates inorganic fertilizers.

population from the more highly populated areas to the less populated area. The move enables full advantage to be taken of the springs for irrigation during the dry season. The global effect of this measure on total income is small; average per capita income increases by only 4 percent (Figure 5.36). This is because, in the baseline scenario, the development of vegetable production helps small farmers obtain higher incomes, while the inequitable distribution of land is also compensated through the labor market. This simulated land reform leads to slightly more erosion because a larger area is cultivated (Figure 5.37).

Dairy Farming

The possibility of producing and selling milk requires the organization of a collection system by a milk processing factory. If these conditions are introduced into the model, specialized dairy farming appears in 1983 when the road is built, to become one of the main production activities. It also significantly increases per capita income (Figure 5.38). These changes rapidly boost the number of cattle in the microwatershed to 700 units (almost all mules and oxen are replaced). More than 80 tons of maize and 20 tons of feed concentrate are purchased every year to fulfill local needs. Small farmers' per capita incomes are increased to the same level as ranchers' incomes, although their different resource endowments foster specialization, with small farmers producing milk and large ranchers producing meat. Much of the present cropland is turned into pasture and the vegetable area is reduced

Figure 5.36 Simulated per capita income: Alternative scenarios for land reform

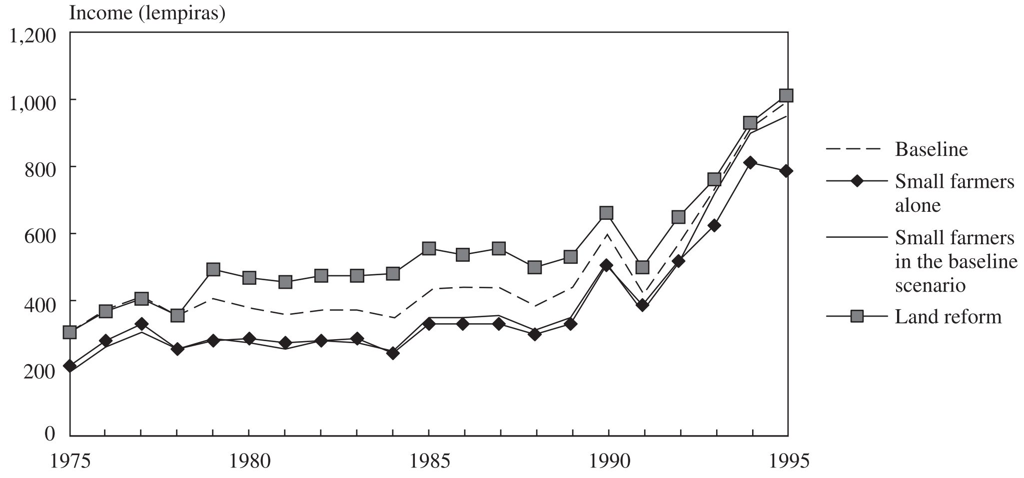


Figure 5.37 Simulated erosion: Alternative scenarios for land reform

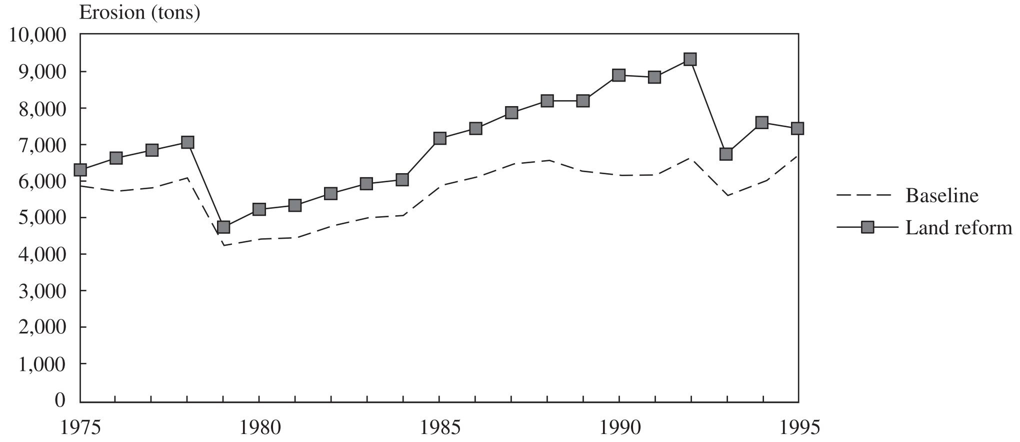
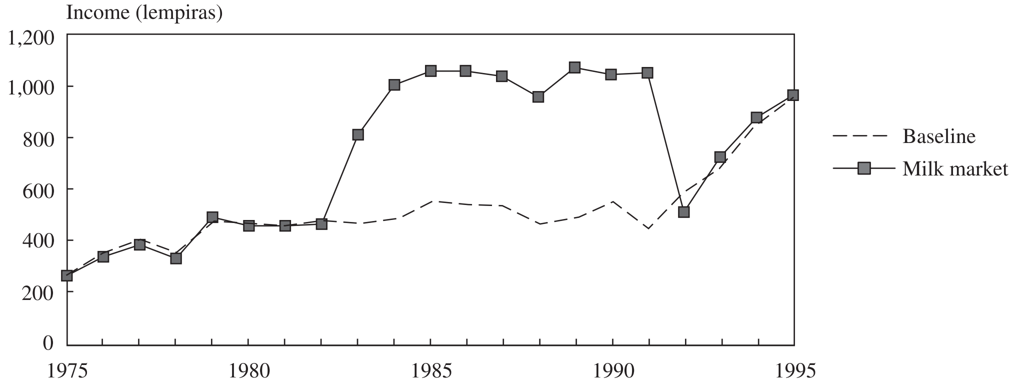


Figure 5.38 Simulated per capita income: Scenario with dairy production



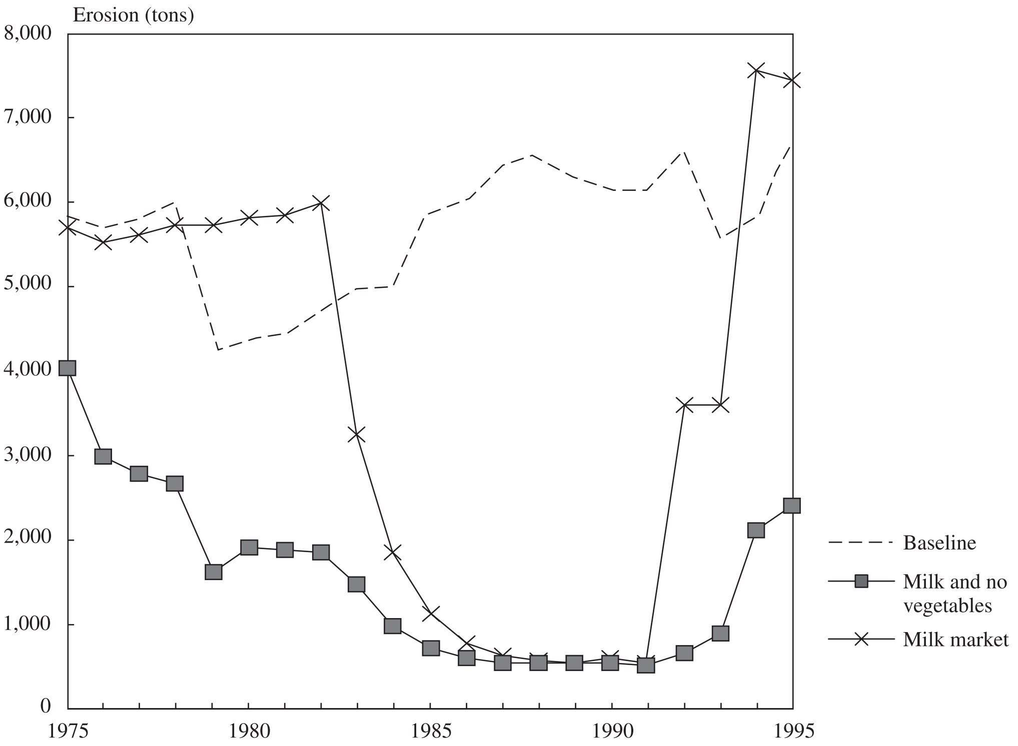
considerably, farmers growing only irrigated onions during the dry season. This new land use produces very low levels of erosion (Figure 5.39). However, in 1992 the model abandons milk production because of competition from vegetables after their prices have increased. At that point, small farmers sell all their cattle.

This simulation illustrates the competition between two labor-intensive activities. The current prices of vegetables make it difficult to sustain milk production in the area. Furthermore, milk and vegetable production are not complementary because both require water and labor. Milk production would be more likely to succeed in areas that have good market access but less favorable conditions for vegetable production.

Conclusion about Policy Interventions

The most recent policy interventions in La Lima have had a positive impact on incomes. Market liberalization, road construction, the potable water distribution system, crop variety improvement, and extension services have all helped to increase incomes. However, the simulations suggest that exclusive use of organic fertilizer, a land reform, and the development of dairy production would not have been successful. This is because intensive vegetable production requires chemical fertilizers in order to provide an important income-earning opportunity for small farms. Moreover, vegetable production is more profitable than dairy production.

Figure 5.39 Simulated erosion: Scenarios with new markets



The simulated policy interventions show a contrasting impact on erosion. Liberalization slightly reduces erosion because the simulated liberalization promotes higher production on a smaller area. Dairy farming decreases erosion to a very low level because pastures have a much lower level of erosion than crops, especially horticultural crops. The non-use of chemical fertilizers increases erosion because farmers will have to plant a larger area to compensate for the lower yields. Land reform slightly increases erosion because farmers will be able to spend more time cropping and less time walking to distant fields. These results show that, in watersheds where erosion is a serious concern, it would be wise to improve commodity prices, promote dairy production instead of horticulture, increase the use of fertilizers on cropland, and avoid a land reform that is likely to convert pastures into cropland.

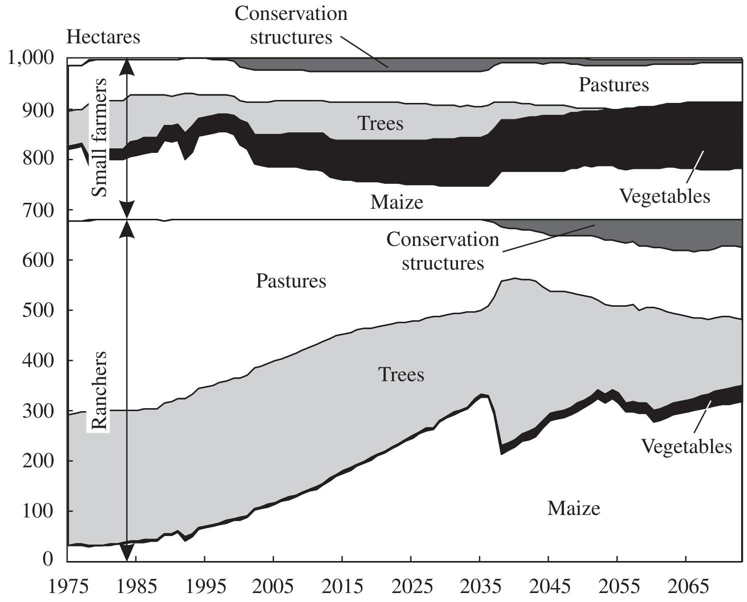
Forward-Looking Scenarios

In the final section of this chapter we analyze four scenarios for the future. First is a baseline scenario extending over 100 years, from 1975 to 2075. Its key assumptions are that (a) population increases at 3 percent per year, (b) the crop response to fertilizers continues to increase exogenously depending upon the type of crop, and (c) prices remain constant after 1995. Given this baseline case, three scenarios are run corresponding to different assumptions about the prices for vegetables, for all crops, and for inorganic fertilizers. These simulations cover the period 1995–2015.

Forward-Looking Baseline Scenario

The baseline scenario is run to assess the effect of erosion over the very long term. Figure 5.40 shows how growing population pressure will lead to greater cultivation. If relative prices remain constant, large ranchers located in the upper, less irrigated zone of the microwatershed eventually become maize producers by hiring an increasing number of small farmers. Small farmers, while producing maize with ranchers, will expand vegetables on their own land. Pasture areas decrease to the benefit of maize and forest. Technological progress in crop productivity compensates for population growth and helps maintain per capita incomes. Over time, the value of land increases while the value of labor stagnates.

Figure 5.40 Simulated land use: Long-term baseline scenario



Soil erosion remains relatively constant (Figure 5.41) until the steeper slopes are cultivated, creating dramatic erosion that depletes the soils. However, by 2060 erosion decreases to less than 1 ton per hectare, thanks to the construction of conservation structures (Figure 5.42); terraces are constructed on the steeper slopes while grass strips are constructed on the medium slopes.

The per capita incomes of the different categories of farmers increase over time but become less equitable (Figure 5.43). Small farmers' income increases slowly once they have exploited all their opportunities. They obtain part of their income by selling labor to large ranchers to produce maize. Ranchers increase their income by expanding the maize area.

Figure 5.41 Simulated erosion by slope: Long-term baseline scenario

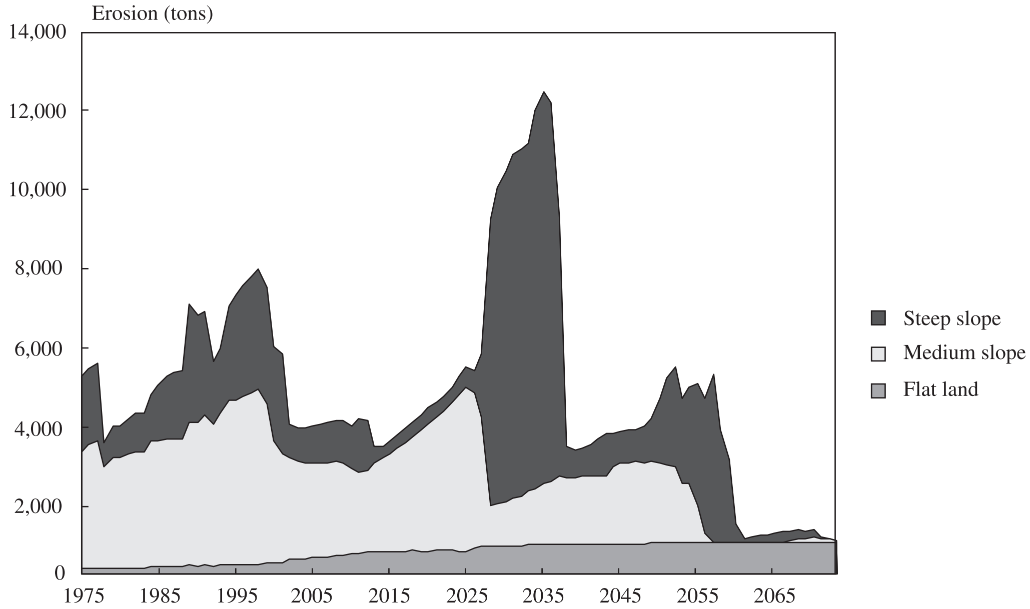


Figure 5.42 Simulated conservation structures: Long-term baseline scenario

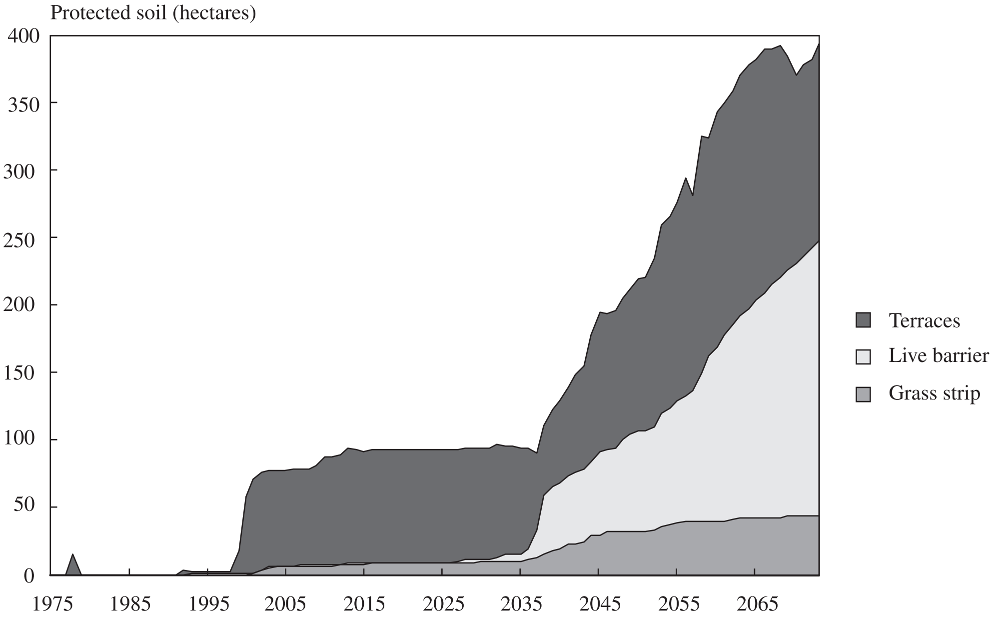
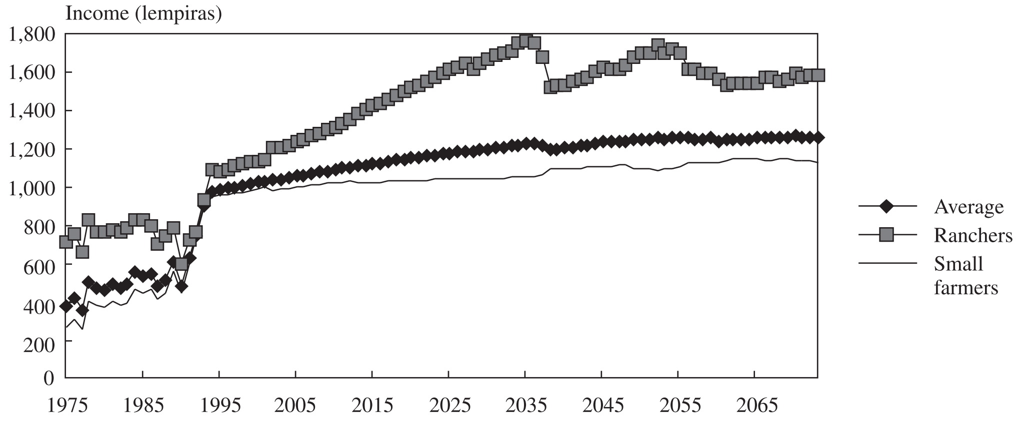


Figure 5.43 Simulated per capita income: Long-term baseline scenario



Scenario with Decreasing Vegetable Prices

The current high prices of vegetables are probably a short-term reaction to recent policy changes, such as the devaluation of the local currency and the ending of price controls. As more communities increase vegetable production, prices are likely to fall to lower levels. Thus, one scenario involves vegetable prices declining continuously at a rate of 3 percent per year over the next 80 years. The effect of such a decline is to decrease slightly the area of vegetables instead of increasing it, as in the baseline scenario where prices remain constant. The maize area increases at approximately the same pace as population growth (2.5 percent per year). Maize yields increase slightly owing to the adoption of better varieties, but farmers use progressively less inorganic fertilizer per unit of land. Per capita incomes decrease continuously by 1.4 percent per year on average (Figure 5.44). Erosion also goes down because the model decreases the area planted to rainy season vegetables, while keeping constant the area of dry season vegetables (Figure 5.45).

Scenario with Decreasing Prices for all Crops

This scenario assumes that both maize and vegetable prices decline by 3 percent per year. The model reacts by progressively reducing the maize area. Under these assumptions, per capita incomes in 2015 plummet to 56 percent lower than in the baseline scenarios (Figure 5.44). However, soil erosion declines to very low levels because the sloped cropped areas are progressively returned to pasture and conservation structures are built on the medium slopes (Figure 5.45).

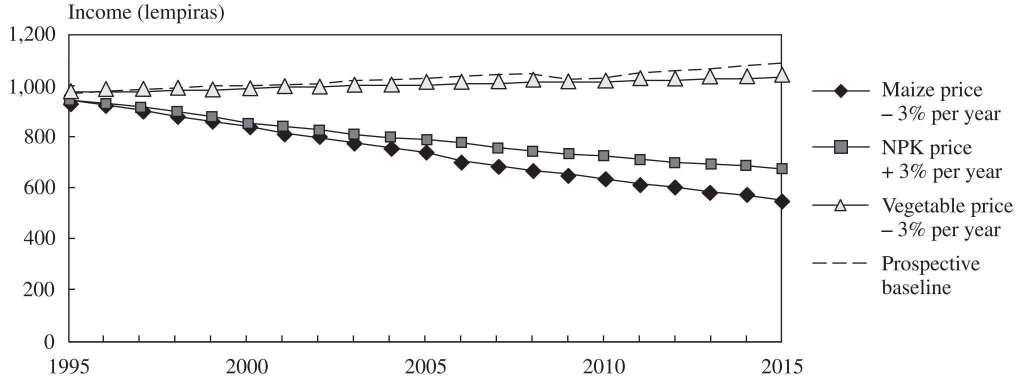
Scenario with Increasing Inorganic Fertilizer Prices

Increases in the price of inorganic fertilizers are plausible because the world supply of nonrenewable nutrients, such as potash and phosphates, might become scarcer. An increase in fertilizer prices by 3 percent per year reduces per capita incomes but has much less of an effect than a decrease in crop prices (Figure 5.44). Erosion is slightly higher in this scenario because the model applies less fertilizer and expands the crop area (Figure 5.45). Vegetable production, which requires a high level of inorganic fertilizers, does not increase, unlike in the base scenario.

Conclusion about the Effect of Future Prices

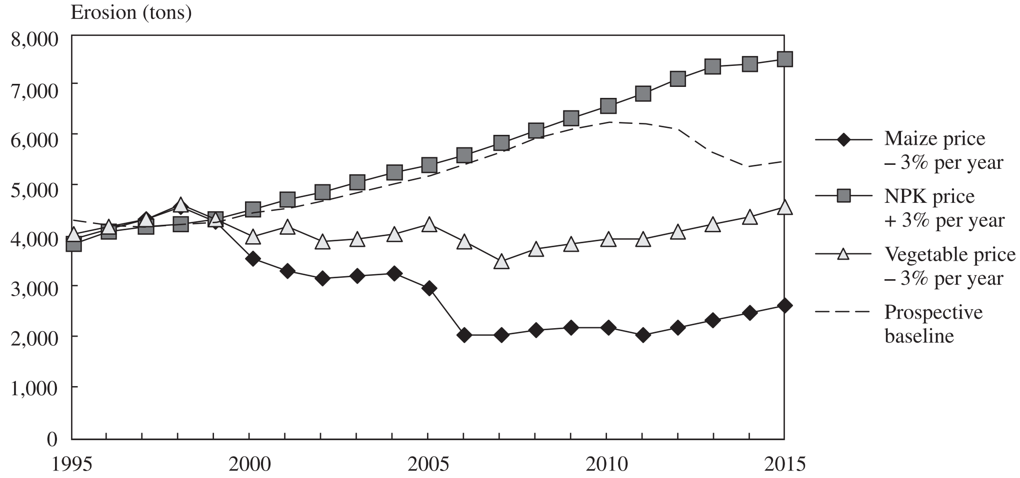
For communities dependent on vegetable production, the future prices of maize will be as important as the prices of vegetables and

Figure 5.44 Simulated per capita income: Alternative scenarios for prices



Note: NPK indicates inorganic fertilizers.

Figure 5.45 Simulated erosion: Alternative scenarios for prices



Note: NPK indicates inorganic fertilizers.

fertilizers in determining their levels of income. However, the profitability of vegetables will remain high even if prices decline, particularly if varietal improvements continue to compensate for population growth and price reduction (a reasonable assumption given that the genetic materials for maize, potato, and other vegetables have improved steadily over the past decades and that adoption of these new seeds has been rapid in areas connected to the market). On the other hand, the current downsizing of the national research and extension services may negatively affect the rate of diffusion and adoption, leading to high costs for producers and consumers alike in the future.

Prices will also indirectly affect soil erosion rates. The forward-looking baseline scenario suggests that erosion will continue to increase if prices remain constant. However, if commodity prices decline, then erosion will decline because farmers will reduce their production of vegetables during the rainy season, which is when most soil erosion occurs. Conversely, an increase in inorganic fertilizer prices will lead to more erosion because farmers will use less fertilizer, obtain lower yields, and increase their cropped area.

CHAPTER 6

General Conclusions

The results of the bioeconomic model presented in this report helped us to discuss a number of induced innovation hypotheses. Many of the results were similar to our initial hypotheses, but some of the results challenged our expectations.

The simulation results for scenarios with differing assumptions about population growth are in accordance with the hypothesis that, *ceteris paribus,* population growth leads to lower per capita incomes. However, technology improvements such as irrigation, a switch to high-yielding varieties, or better access to markets can help overcome diminishing returns to labor. This is precisely what occurred in La Lima, where the factors that contributed most to income increases over the past 20 years were the switch to improved maize varieties, the adoption of irrigation and fertilization technologies, and a favorable market situation for vegetables.

The second hypothesis relates to the effects of population increases on natural resources conditions. The model showed whether the hypothesis of a U-shaped function held up in La Lima.[21] The simulations indeed found a relationship of this type, but only after almost tripling the population level in the microwatershed, a condition that is unlikely to occur any time soon in La Lima. There is very little evidence of a U-shaped relationship to date in La Lima. There are two reasons for this. First, given the intensification of production, population increases had relatively small effects on expanding the cropped area—resources tended to be concentrated in a relatively small area. True, there were signs of increasing environmental deterioration in La Lima, but these were mainly found on horticultural plots during the rainy season. In other words, recent environmental problems were due more to the development of vegetable production than to population growth. Second, farmers did not react to growing degradation by investing in land improvements, as was expected. It seems that farmers did not feel the need to improve their practices, as long as the area affected and the severity of degradation were marginal. In other words, conditions in La Lima never became extreme enough to trigger the type of relationship described by the U-shaped function.

The results also show that improved access to markets increases per capita incomes. Following the opening of the road and greater access to regional markets, local farmers under-

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[21] To recall, this hypothesis states that natural resource conditions will decline to a point where forgone benefits are greater than the costs of investments. At that point farmers can be expected to start investing in land improvement techniques in order to offset those losses.

took a series of structural transformations that enabled them to benefit from the advantageous prices offered by nontraditional crops. As shown by our model, however, market access is not sufficient in and of itself; improved production techniques, appropriate price policies, and climatic conditions also played a key role in permitting this income increase.

The second part of this hypothesis, which associates market access with land investments, was not verified. Improved access to markets does not necessarily promote land conservation because the value of land does not perforce increase with greater market access. This is well illustrated in our model of La Lima, where the profitability of horticultural production—a labor-intensive and land-saving production strategy—favors an increase in the value of labor relative to land, which makes labor-intensive land investments less likely. In La Lima, as already noted, the severity of degradation was not sufficient to encourage costly investments. If land were more scarce, on the other hand, the pressure would be greater and investments would be more likely.

The last hypothesis stated that agroecological conditions are important factors in determining incomes and natural resource conditions. The simulations indeed show that the results are relevant only for villages with similar agroecological conditions. Our simulations demonstrate that incomes would be much lower, and degradation much higher, if vegetable production had not been possible for ecological reasons. Farmers would have been reduced to adopting extensive land use strategies. This result acquires its importance when brought into the context of the “pathways of development” concept, which states that the pathway chosen is a function of a complex set of conditioning factors, in which agroecology plays a fundamental role. In other words, notwithstanding the economic advantages of horticultural production, this strategy is not suited to all contexts.

A policy approach based on a notion of pathways of development would implicitly recognize such limitations, thereby directing resources where they will have their greatest impact. Again, La Lima offers a good example of this. This community clearly benefited from the main agricultural policies enacted in Honduras lately: market and price liberalization, infrastructure development (road construction, drinking water system), and extension services (crop variety improvement and irrigation systems) all helped secure the positive results documented in this report. Note, however, that the simulations also suggested that, keeping everything else constant, alternative policies that may have positive effects in other situations—such as a land reform, the development of dairy production, the stimulation of organic farming—would probably not have been successful in La Lima. This emphasizes the importance of recognizing the diversity of complex production environments and their implications for understanding the differential impact of some policies on distinct areas.

Modeling exercises such as this one assist in understanding the mechanics by which policies have an impact, not only in the present but also in the future. For instance, our forward-looking baseline scenario suggests that erosion will continue to increase if real prices remain constant. If commodity prices decline, however, erosion will decline because farmers will reduce their production of vegetables during the rainy season, which is when most soil erosion occurs. Conversely, an increase in inorganic fertilizer prices will lead to more erosion because farmers will use less fertilizer, obtain lower yields, and increase their cropped area.

APPENDIX

Mathematical Statement of the Microwatershed-Level Linear Programming Model

The model maximizes the present value of future utility for the whole watershed. There are three zones and two types of household, which leads to six groups of farmers. Each group has access to three types of soil varying by their slope. This leads to 18 land units. The constraints are land, labor, capital, food, fuelwood, forage, soil fertility, soil depth, and water. The main activities are crops, meat production, milk production, forestry, coffee production, and off-farm activities.

Endogenous variables are capitalized, coefficients are in small letters, and indices are subscripts.

Sets

a	tree species (a_1 pines, a_2 traditional coffee, a_3 improved coffee)
c	crop type (c_1 maize, c_2 irrigated crops, c_3 potatoes, c_4 tomatoes)
d	thresholds in fertilization efficiency, in the effect of soil depth deficit, and in the effect of water stress
h	household type (h_1 ranchers, h_2 small farmers)
k	three soil conservation types (terraces, king grass, and grass strip)
l	livestock type (l_1 cattle and calves, l_2 oxen, l_3 mules)
o	three soil types depending on the slope
p	four periods within each year
plast	last period of year
r	discount rate

s	three zones of the microwatershed depending on their altitude
t	time in years
tlast	last year of the planning horizon
y	age of trees

Variables

BUY	quantity of purchased grain in tons
CASH	cash expenditure on various farm costs in local currency
CASHNPK	cash expenditure on conventional inputs in local currency
COMPOST	compost in tons
CONSER	conservation structures in hectares
CORRAL	manure produced by corralling activity in tons
CROP	crop area in hectares
CUTCONS	abandoned crop soil conservation structures
CUTCROP	abandoned crop area in hectares
CUTGRAS	reduction of grass area in hectares
CUTIRRI	removal of irrigation equipment for 1 hectare
CUTREE	tree cutting in cubic meters; the area is replaced by crops
CUTREEG	tree cutting in cubic meters; the area is replaced by grass
DMEC	day of transportation by mule
EMIG	number of permanent emigrants
EROSION	erosion volume in cubic meters
EROSIONG	erosion volume under forest and pasture in cubic meters
FAMLAB	family labor in days
FEED	grain for feed in tons
FOOD	grain consumed by the microwatershed population in tons
GRASS	grass area in hectares
GROUND	soil volume above subsoil in cultivated areas in cubic meters
GROUNDG	soil volume above subsoil under pastures and forest in cubic meters
HELPIN	days of labor paid by one group to farmers from another group located in the same zone
HELPINS	days of labor paid by one group to farmers from another group located in another zone
HELPOUT	days of labor sold by farmers to another group within the zone
HELPOUTS	days of labor sold by farmers to another group in another zone
HOEAREA	crop area that is cultivated by hand in hectares
IMMIG	number of permanent immigrants
IRRI	irrigated area in hectares

KEROSEN	kerosene equivalent of 1 cubic meter of fuelwood
LABOR	total labor required in the microwatershed in days
LEISURE	leisure days
LIV	number of livestock in tropical units
MANURE	manure in tons
MEC	number of mechanization units, such as plows
MECAREA	area plowed with oxen in hectares
MIGRANT	number of temporary (day) workers from outside the community
MILK	total milk production in tons
NEWCONS	new conservation structures in hectares
NEWCROP	new cropped area in hectares
NEWGRAS	new pasture
NEWIRRI	new irrigated area in hectares
NEWLIV	purchased livestock in standard tropical units
NEWMEC	number of new mechanization units, such as plows
NEWTREE	new tree plantation in cubic meters of wood
NITORG	organic nitrogen in tons
NPK	inorganic fertilizers in tons
POP	population of the microwatershed
PURC	purchased animal food in tons
RESFEED	crop residues used as feed in tons
RESIDU	crop residues used for compost and manure in tons
SAVING	savings in local currency
SEED	seed from the last harvest in tons
SELCROP	crop sale in tons
SELLIV	livestock units sold
SELMEC	mechanization units sold
SELTREE	tree volume sold
SOILDEF	soil depth deficit in cubic meters
STOCK	grain stocks in tons
STREAM	volume of water available in the streams of one zone in cubic meters
STRESS	plant water deficit in cubic meters
SURP	forage surplus in forage units
TREE	trees in cubic meters
TPROD	total crop production in tons
TUTIL	total utility in local currency
UTIL	annual utility in local currency
WATER	water used for irrigation
WOOD	wood volume in cubic meters

Coefficients

acth(p)	day of labor available per period

agarea	area covered by 1 cubic meter of tree in hectare
areal(k)	area occupied by land conservation structures in hectares per hectare
area(h,s,o)	cultivable area in hectares
avgy(c,o)	average crop yields in tons per hectare
cons(p)	cereal consumed per period in tons per person
consd(p)	cereal consumed per period in tons per adult migrant
cost(c)	cost of pesticides and new seeds in local currency
cr(c)	yield decrease owing to use of hand tools instead of plow
deadwood(a)	volume of dead wood produced by 1 cubic meter of tree
demand(t)	exogenous demand for agricultural products
depmec	annual rate of depreciation of plow and weeder
deprirr	annual rate of depreciation of irrigation devices
depth(h,s,o)	agricultural soil volume in cropped area in cubic meters per hectare
depthg(h,s,o)	agricultural soil volume under pasture and forest in cubic meters per hectare
distf	average distance between farms within a zone in kilometers
distf	average distance between two zones in kilometers
dstfield(s)	average distance of field from the farm in kilometers
dstroad(s)	average distance of farm from the road in kilometers
dpline	coefficient of depletion of land conservation structures in hectares
eros(o,c)	erosion in cubic meters per hectare
erosf	erosion under 1 hectare of forest in ton
erosg(o,c)	erosion under pasture and forest in cubic meters per hectare
famil(p)	minimal living expenses per family member in local currency
form(o)	annual rate of soil formation in tons per hectare
harv(c,p)	harvest period—0 for no; 1 for yes
house(em)	upper bound for emigration
house(imm)	upper bound for immigration
house(mig)	upper bound for temporary migration
liveh(l)	natural growth rate of the livestock herd
lmec	maximum area worked by a plow per season
milkp	production per cow in liters
mule	weight potentially transported by a mule in tons per kilometer per day
nitcom(p)	tons of organic nitrogen in 1 ton of compost
nitcon	nitrogen content of NPK

nitcor(p)	tons of organic nitrogen in 1 ton of corral product
niteff(c,d)	additional production due to chemical fertilizers (tons per ton of nitrogen)
niteffo(c,d)	additional production due to organic nitrogen use (tons per ton of nitrogen)
nitlim(c,d)	threshold of organic nitrogen effect on yield (tons per ton of nitrogen)
nitnctg(p)	tons of organic nitrogen available for the next crop after the preparation of a pasture
nitnctr(p)	tons of organic nitrogen made available for crops where trees have been cut
nitnman(p)	tons of organic nitrogen in 1 ton of manure
opport(p)	opportunity cost of leisure in local currency per day
pcow	proportion (percentage) of productive cows
per(p)	days of labor available per adult
popg	population growth rate
price(a,y)	price of 1 cubic meter of fuelwood
price(c,p)	crop prices per period in local currency per ton
price(l)	livestock prices per period in local currency per unit
pricebuy	price of purchased grain in local currency
pricecoffe	price of 1 ton of coffee in local currency
priceirr	price of one irrigation system in local currency
priceker	price of kerosene in local currency
pricemec	price of a plow in local currency
pricemilk	price of 1,000 liters of milk in local currency
pricemirr	yearly price for the maintenance of one irrigation system in local currency
pricenc(a)	price per plant of coffee in local currency
pricenew	price of young coffee trees
pricenpk	price per ton of chemical fertilizer
pricepur	price of purchased feed in local currency
refus	dung produced by one unit of livestock in tons
resid(c)	crop residues in tons per ton of yield
rsd	tons of crop residues to produce 1 ton of manure
seedn(c,p)	required quantity of seed in tons per hectare
soildp(d)	soil depth limit; below this yields are affected
soiler(c,d)	soil erosion effect on yields
soilf(o)	erosion limitation by 1 hectare of forage crop
soilg(o)	erosion limitation by 1 hectare of grass
soill(o,k)	reduction in erosion by land conservation structures in cubic meters per hectare
soiln	volume of soil in cubic meters protected against erosion

	by the application of 1 ton of inorganic fertilizers.
soilo	volume of soil protected against erosion by the application of 1 ton of organic fertilizers
soilp(c,d)	production loss from soil loss in tons per ton of soil deficit
soilt(o)	erosion limitation by 1 cubic meter of trees
soilv(o)	threshold of soil volume below which yields are affected in cubic meters
spoil(c,p)	rate of depreciation of grain stocks during period *p*
springs(s)	volume of water coming from springs
suit(h,s,o)	fraction of land suitable for irrigation in hectares
tract	units of livestock necessary per equipment
uf(l,p)	forage units required by one unit of livestock
uf(o,p)	forage units provided by 1 hectare of pastures on different types of soil
uf(p,c)	forage units provided by 1 ton of grain
ufprc(p)	forage units provided by 1 ton of purchased feed
ufrs(p,c)	forage units provided by 1 ton of residues
ufsrp(p)	fraction of pasture grass or residue carried over into next period
wage(p)	wage of off-farm activities in local currency per period
watc	maximum volume of water in cubic meters that can be distributed by one set of sprinklers
watef(c,d)	effect of water deficit on yields in kilos per cubic meter
watn(c)	water volume required per hectare of crops during the dry season in cubic meters
watp	water volume used by one person during the dry season in cubic meters
wirri	weight of irrigation devices in tons per hectare
wline(k)	weight of the stones necessary for 1 hectare of soil conservation structures
woodn(p)	consumption of wood in cubic meters per person
wwood	weight of 1 cubic meter of wood
yldcof(a)	yield of coffee in tons per hectare

Crop Production

There are two types of farm (*h*) per zone, three zones (*s*), and three types of soil (*o*). In total this makes 18 land units. Each land unit is covered by crops, trees, pasture, and land conservation structures. Crops of the dry season are constrained later by the irrigable area.

$$\sum_{c=1}^{C} CROP_{h,s,o,c,t} + \sum_{a=1}^{A} \sum_{y=1}^{Y} TREE_{h,s,o,a,y,t} + GRASS_{h,s,o,t} + \sum_{k=1}^{K} areal_{k} \cdot CONSER_{h,s,o,k,t} = area_{h,s,o}.$$

Land use change includes the expansion or the diminution of the cropped and the pasture areas. Corresponding equations for trees and land conservation practices follow.

$$CROP_{h,s,o,c,t-1} - CUTCROP_{h,s,o,c,t} + NEWCROP_{h,s,o,c,t} = CROP_{h,s,o,c,t}.$$

$$GRASS_{h,s,o,t-1} - CUTGRAS_{h,s,o,t} + NEWGRAS_{h,s,o,t} = GRASS_{h,s,o,t}.$$

Annual crop production is a function of yield (*avgy*) and area (*CROP*). There is a basic yield (*avgy*) that depends upon the type of soil (*o*) and the type of crop (*c*). This basic level of production can be increased by applying chemical nitrogen (*nitcon* · *NPK*) or organic nitrogen (*NITORG*). Conversely, production would decrease with more superficial land preparation by hand (*HOEAREA*), an insufficient soil depth (*SOILDEF*), erosion (*EROSION*), or a water deficit (*STRESS*).

$$\begin{aligned} TPROD_{h,s,o,c,t} &= avgy_{o,c} \cdot CROP_{h,s,o,c,t} \\ &\quad - cr_{c} \cdot HOEAREA_{h,s,o,c,t} \\ &\quad + \sum_{d=1}^{D} niteff_{c,d} \cdot nitcont_{c} \cdot NPK_{h,s,o,c,d,t} \\ &\quad + \sum_{d=1}^{D} niteff_{c,d} \cdot NITORG_{h,s,o,c,d,t} \\ &\quad - \sum_{d=1}^{D} soilp_{c,d,} \cdot SOILDEF_{h,s,o,c,d,t} \\ &\quad - soiler_{c,d} \cdot EROSION_{h,s,o,c,t} \\ &\quad - \sum_{d=1}^{D} watef_{c,d} \cdot STRESS_{h,s,o,c,d,t} \end{aligned}$$

During each period, the initial stock of crop products is sold, consumed by humans and animals, and used as seed. A fraction of the initial stock is lost to spoilage. The remaining stock is carried over into the next period. Crops are harvested, then the harvest is sold or can be stored.

$$\begin{aligned} & spoil_{c,p} \cdot STOCK_{h,s,c,p-1,t} + harv_{c,p} \\ & \cdot TPROD_{h,s,o,c,t} - SELCROP_{h,s,c,p,t} \\ & - FOOD_{h,s,c,p,t} - FEED_{h,s,c,p,t} \\ & - SEED_{h,s,c,p,t} = STOCK_{h,s,c,p,t} \end{aligned}$$

Between years, the remaining stock is carried over into the first period of the next year.

$$\begin{aligned} & spoil_{c,p} \cdot STOCK_{h,s,c,plast,t-1} + harv_{c,p} \\ & \cdot \sum_{o=1}^{O} (TPROD_{h,s,c,t} - SEED_{h,s,o,c,t}) \\ & - SELCROP_{h,s,c,plast,t} \\ & - FOOD_{h,s,c,plast,t} \\ & - FEED_{h,s,c,plast,t} - SEED_{h,s,c,plast,t} \\ & = STOCK_{h,s,c,plast,t}. \end{aligned}$$

There is a given amount of seed per hectare of crop.

$$seedn_{c,p} \cdot \sum_{o=1}^{O} CROP_{h,s,o,c,t} = \sum_{p=1}^{P} SEED_{h,s,c,p,t}.$$

Consumed maize is produced or bought. The population that migrated temporarily out of the microwatershed is deducted during the migration period.

$$FOOD_{h,s,c_2,p,t} + BUY_{h,s,c_2,p,t} \geq cons_{p} \cdot POP_{h,s,t} - consd_{p} \cdot MIGRANT_{h,s,p,t}$$

Crop sales are limited by the number of regular traders and their transportation capacity (*demand*).

$$\sum_{h=1}^{H} \sum_{s=1}^{S} \sum_{c=1}^{C} SELCROP_{h,s,c,p,t} \leq \sum_{c=1}^{C} demand_{c,p}.$$

Soil

The initial volume of cultivated soil increases through natural soil formation (*form*) but decreases through erosion (*EROSION*). One new hectare of crop (*NEWCROP*) adds the average volume of that soil (*depth*) at the beginning of the simulation.

$$(1 + form_{s,o}) \cdot GROUND_{h,s,o,t-1}$$
$$\sum_{c=1}^{C} (EROSION_{h,s,o,c,t}\ depth_{s,o}$$
$$\cdot\ CUTCROP_{h,s,o,c,t} + depthg_{s,o}$$
$$\cdot\ NEWCROP_{h,s,o,c,t}) = GROUND_{h,s,o,t}.$$

Similarly, the initial volume of soil under forest and pastures increases through natural soil formation (*form*) but decreases through erosion (*EROSIONG*). Conversely, one new hectare of crop (*NEWCROP*) reduces the average volume of that soil (*depth*).

$$(1 + form_{s,o}) \cdot GROUNDG_{h,s,o,t-1}$$
$$EROSIONG_{h,s,o,t} + depth_{s,o} \cdot$$
$$\sum_{c=1}^{C} CUTCROP_{h,s,o,c,t} - depthg_{s,o}$$
$$\sum_{c=1}^{C} \cdot\ NEWCROP_{h,s,o,c,t}$$
$$= GROUNDG_{h,s,o,t}.$$

Erosion in the cultivated area is the result of cropping activities (*CROP*) but is reduced by soil conservation structures (*CONSER*) and by fertilization (*NPK, NITORG*).

$$\sum_{c=1}^{C} EROSION_{h,s,o,c,t} = \sum_{c=1}^{C} \Big(eros_{o,c}$$
$$\cdot\ CROP_{h,s,o,c,t}\ soiln_{o} \cdot \sum_{d=1}^{D} NPK_{h,s,o,c,d,t}$$
$$soil_{o} \cdot \sum_{d=1}^{D} NITORG_{h,s,o,c,d,t} \Big)$$
$$\sum_{k=1}^{K} soill_{o,k} \cdot CONSER_{h,s,o,k,t}.$$

Another equation determines erosion in pasture and forest:

$$EROSIONG_{h,s,o,t} = erosg_{o} \cdot GRASS_{h,s,o,t}$$
$$+ erosf_{o} \cdot agarea_{a,y} \cdot \sum_{a=1}^{A} \sum_{y=1}^{Y} TREE_{h,s,o,a,y,t}.$$

If the ground volume under a crop (*GROUND*) decreases below a certain amount per hectare (*soilv*), a deficit will appear (*SOILDEF*).

$$GROUND_{h,s,o,t} \geq soilv_{s,o} \cdot \sum_{c=1}^{C} CROP_{h,s,o,c,t}$$
$$- \sum_{c=1}^{C} \sum_{d=1}^{D} SOILDEF_{h,s,o,c,d,t}.$$

The following equation determines a different level of deficit per hectare (*SOILDEF*), where *soildp* are different volumes of soil per hectare.

$$SOILDEF_{h,s,o,c,d,t} \leq soildp_{d} \cdot CROP_{h,s,o,c,t}.$$

Initial soil conservation structures (*CONSER*) deteriorate (*dpline*) from climatic factors, and may be maintained or extended by farmers (*NEWCONS*).

$$(1 - dpline_{k}) \cdot CONSER_{h,s,o,k,t-1}$$
$$+ NEWCONS_{h,s,o,k,t} - CUTCONS_{h,s,o,k,t}$$
$$= CONSER_{h,s,o,k,t}.$$

The area protected against erosion is smaller than the rainy season cropped area.

$$CONSER_{h,s,k,t} \leq \sum_{c=1}^{C} CROP_{h,s,o,c,t}.$$

Water Modeling

The following equation accounts for change in the irrigated areas (tubes and sprinklers).

$$IRRI_{h,s,t} = IRRI_{h,s,t-1} + NEWIRRI_{h,s,t}$$
$$- CUTIRRI_{h,s,t}$$

Each set of sprinklers has a limited aspersion capacity during the dry season.

$$WATER_{h,s,t} = watc \cdot IRRI_{h,s,t}$$

The irrigated area is equal to or lower than the area suitable for irrigation.

$$IRRI_{h,s,t} \leq \sum_{o=1}^{O} suit_{h,s,o} \cdot area_{h,s,o}$$

Irrigation volume is greater than the crop requirement. If not, water stress occurs.

$$WATER_{h,s,t} \leq \sum_{o=1}^{O} \sum_{c=1} \bigg(watn_{c} \cdot CROP_{h,s,o,c,t} - \sum_{d=1}^{D} STRESS_{h,s,o,c,d,t} \bigg)$$

Water from the stream is used for irrigation (*WATER*) and by the population (*watp* · *POP*). The remaining water continues in the next zone located downstream.

$$springs_{s} + STREAM_{h,s-1} - WATER_{h,s,t} - watp \cdot POP_{h,s,t} = STREAM_{h,s,t}.$$

Population and Labor

The population at the end of each year is the beginning population (POP_{t-1}) adjusted for growth (*popg*), plus immigrants (*IMMIG*) minus emigrants (*EMIG*). Permanent emigration and immigration are limited to a fraction of the population.

$$(1 + popg) \cdot POP_{h,s,t-1} + IMMIG_{h,s,t} - EMIG_{h,s,t} = POP_{h,s,t}.$$

For the sake of simplicity, the labor time of the different farm activities is aggregated into one variable (*LABOR*). Labor time (*LABOR*), migration (*per*(*p*) · *MIGRANT*) time, leisure time (*LEISURE*), and labor time on other farms from the same zone (*HELPOUT*), plus labor on other farms from other zones (*HELPOUTS*) and a coefficient representing the time to walk from one farm to the other within a zone (*distf*) and between two zones (*distfs*) have to be equal to the family labor (*FAMLAB*) plus the labor from other farmers from the same zone (*HELPIN*) and from other zones (*HELPINS*).

$$LABOR_{h,s,p,t} + per_{p} \cdot MIGRANT_{h,s,p,t} + LEISURE_{h,s,p,t} + distf \cdot HELPOUT_{h,s,p,t} + distfs \cdot HELPOUTS_{h,s,p,t} = FAMLAB_{h,s,t} + HELPIN_{h,s,p,t} + HELPINS_{h,s,p,t}$$

Family labor plus off-farm labor is less than the total work days available.

$$FAMLAB_{h,s,p,t} + HELPOUT_{h,s,p,t} + HELPOUTS_{h,s,p,t} + MIGRANT_{h,s,p,t} = \angle = acth_{p} \cdot POP_{h,s,t}$$

The following equation ensures the equilibrium of the supply of and demand for wage labor within the microwatershed.

$$\sum_{h=1}^{H} \sum_{s=1}^{S} HELPINS_{h,s,p,t} = distfs \cdot \sum_{h=1}^{H} \sum_{s=1}^{S} HELPOUTS_{h,s,p,t}.$$

The following equation ensures the equilibrium of the supply of and demand for wage labor within each zone.

$$\sum_{h=1}^{H} HELPIN_{h,s,p,t} = \sum_{h=1}^{H} distf \cdot HELPOUT_{h,s,p,t}.$$

Soil Fertility Modeling

Organic nitrogen comes from different types of manuring techniques. Tree cutting (*CUTREE*) also produces nitrogen as the first year of cultivation in a deforested area produces better yields. Similarly, cultivation after pasture conversion (*CUTGRAS*) produces better yields.

$$\sum_{c=1}^{C} \sum_{d=1}^{D} NITORG_{h,s,o,c,d,t} \leq \sum_{p=1}^{P} \bigg(nitnman_{p}$$

$$
\begin{aligned}
&\cdot\, MANURE_{h,\,s,\,o,\,p,\,t} + nitcor_{p} \\
&\cdot\, CORRAL_{h,\,s,\,o,\,p,\,t} + nitcom_{p} \\
&\cdot\, COMPOST_{h,\,s,\,o,\,p,\,t} + nitnctr_{p} \\
&\cdot \sum_{a=1}^{A} \sum_{y=1}^{Y} CUTREE_{h,\,s,\,o,\,a,\,p,\,y,\,t} + nitnctg_{p} \\
&\cdot\, CUTGRAS_{h,\,s,\,o,\,p,\,t}\Big).
\end{aligned}
$$

The equation below determines the thresholds differentiating the effect of organic nitrogen on production. The marginal effect of organic nitrogen applied on a field decreases with the applied amount.

$$
\begin{aligned}
&NITORG_{h,\,s,\,o,\,c,\,d,\,t} + nitcon \cdot NPK_{h,\,s,\,o,\,c,\,d,\,t} \\
&\quad \leq nitlim_{c,\,d} \cdot CROP_{h,\,s,\,o,\,c,\,t}
\end{aligned}
$$

Crop residues (*resid*) are used as feed (*RESFEED*) or as biomass (*RESIDU*) for manure and compost production.

$$
\begin{aligned}
&RESFEED_{h,\,s,\,o,\,c,\,t} + RESIDU_{h,\,s,\,o,\,c,\,t} \\
&\quad \leq resid_{c} \cdot TPROD_{h,\,s,\,o,\,c,\,t}.
\end{aligned}
$$

Manure (*MANURE*) and compost (*COMPOST*) production are limited by the amount of crop residue available (*rsd* • *RESIDU*).

$$
\begin{aligned}
&\sum_{o=1}^{O} \sum_{p=1}^{P} MANURE_{h,\,s,\,o,\,p,\,t} \\
&\quad + \sum_{o=1}^{O} \sum_{p=1}^{P} COMPOST_{h,\,s,\,o,\,p,\,t} \leq rsd_{c} \\
&\quad \cdot \sum_{o=1}^{O} \sum_{c=1}^{C} RESIDU_{h,\,s,\,o,\,c,\,t}.
\end{aligned}
$$

Manure (*MANURE*) and corralling (*CORRAL*) are limited by the number of livestock (*LIV* and *SELLIV*) and their dung (*refus*).

$$
\begin{aligned}
&\sum_{o=1}^{O} \sum_{p=1}^{P} MANURE_{h,\,s,\,o,\,p,\,t} \\
&\quad + \sum_{o=1}^{O} \sum_{p=1}^{P} CORRAL_{h,\,s,\,o,\,p,\,t} \leq refus_{p}
\end{aligned}
$$

$$
\cdot \sum_{l=1}^{L} \left(LIV_{h,\,l,\,s,\,t} + \sum_{p=1}^{P} SELLIV_{h,\,l,\,s,\,p,\,t} \right).
$$

Livestock Modeling

The energy requirements (*uf*) of the resident livestock (*LIV* and *SELLIV*) have to be fulfilled by locally produced forage or purchased feed. The livestock feed concentrate represents only a fraction of the animal diet because animals have minimal fiber requirements. A fraction of the grass or the residues (*SURP*) that have not been consumed during period *p* 1 is carried over into period *p*.

$$
\begin{aligned}
&\sum_{l=1}^{L} uf_{p,l} \cdot (LIV_{h,\,s,\,l.,\,t} + SELLIV_{h,\,s,\,l,\,p,\,t}) \\
&\quad + SURP_{h,\,s,\,p,\,t} \leq \sum_{o=1}^{O} uf_{s,\,p} \cdot GRASS_{h,\,s,\,o,\,t} \\
&\quad + \sum_{c=1}^{C} \sum_{o=1}^{O} uf_{c,\,p} \cdot FEED_{h,\,s,\,o,\,c,\,p,\,t} \\
&\quad + \sum_{o=1}^{O} \sum_{c=1}^{C} ufrs_{o,\,c} \cdot RESFEED_{h,\,s,\,o,\,c,\,t} \\
&\quad + ufprce_{p} \cdot PURC_{h,\,s,\,p,\,t} + ufsrp_{p} \\
&\quad \cdot SURP_{h,\,s,\,plast,\,t}
\end{aligned}
$$

The milk production per cow (*milkp*) multiplied by the proportion of productive cows (*pcow*) in the herd gives the milk production (*MILK*).

$$
milkp \cdot pcow \cdot LIV_{h,\,s,\,l_1,\,t} = MILK_{h,\,s,\,t}.
$$

The area cultivated by plow (*MECAREA*) is limited by the number of plows available (*MEC*) and by their working capacity during the preparation period in hectare (*lmec*).

$$
\sum_{o=1}^{O} \sum_{c=1}^{C} MECAREA_{h,\,s,\,o,\,c,\,t} \leq lmec \cdot MEC_{h,\,s,\,t}.
$$

The crop area must be cultivated with hand tools (*HOEAREA*) or with plows (*MECAREA*).

$$
\begin{aligned}
&MECAREA_{h,\,s,\,o,\,c,\,t} + HOEAREA_{h,\,s,\,o,\,c,\,t} \\
&\quad = CROP_{h,\,s,\,o,\,c,\,t}.
\end{aligned}
$$

The plow (*MEC*) requires two oxen $LIV(l_2)$.

$$tract \cdot MEC_{h,s,t} \le LIV_{h,s,l_2,t}.$$

The number of days of transportation by mule (*DMEC*) has to be lower than the number of days available for one person during each period (*acth*) because transportation by one mule (LIV_{13}) requires the assistance of one person.

$$DMEC_{h,p,t} \le acth_p \cdot LIV_{h,s,13,t}.$$

Inputs, manure, wood, and products have to be transported between the house, the fields, and the market by mule during each season. The transportation capacity is determined by the number of days available for transportation by mule (*DMEC*). These days are multiplied by the ton/kilometer capacity of a mule.

$$\begin{aligned}
&\sum_{o=1}^{O} dstfield_s \cdot (MANURE_{h,s,o,p,t} + dstfield_s \\
&\quad \cdot COMPOST_{h,s,o,p,t}) + \sum_{c=1}^{C} dstroad_s \\
&\quad \cdot SELCROP_{h,s,c,p,t} + dstroad_s \\
&\quad \cdot PURC_{h,s,p,t} + \sum_{o=1}^{O} \sum_{a=1}^{A} dstroad_s \\
&\quad \cdot wwood \cdot SELTREE_{h,s,o,a,p,t} \\
&\quad + dstroad_s \cdot BUY_{h,s,p,t} \\
&\quad + \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{d=1}^{D} (dstfield_s + dstroad_s) \\
&\quad \cdot NPK_{h,s,o,c,d,t} + dstfield_s \cdot harv_p \\
&\quad \cdot \sum_{c=1}^{C} \sum_{o=1}^{O} TPROD_{h,s,o,c,t} \\
&\quad + \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{k=1}^{K} dstfield_s \cdot wline_k \\
&\quad \cdot NEWCONS_{h,s,o,c,k,p,t} \\
&\quad + \sum_{s=1}^{S} \sum_{o=1}^{O} \sum_{c=1}^{C} dstfield_s \cdot RESIDU_{h,s,o,c,t} \\
&\quad + dstfield_s \cdot woodn_p \cdot wwood \cdot POP_{h,s,t} \\
&\quad \le mule \cdot DMEC_{h,s,p,t}.
\end{aligned}$$

The initial number of plows (*MEC*) is reduced through sales (*SELMEC*) and depreciation (*depmec*) or increased through purchases (*NEWMEC*).

$$\begin{aligned}
&(1 + depmec) \cdot MEC_{h,s,t-1} \\
&\quad + \sum_{p=1}^{P} (NEWMEC_{h,s,p,t} - SELMEC_{h,s,p,t}) \\
&\quad = MEC_{h,s,t}
\end{aligned}$$

Forest Modeling

The energy necessary for cooking comes from wood and from kerosene.

$$\begin{aligned}
&\sum_{p=1}^{P} woodn_p \cdot POP_{h,s,t} \le KEROSEN_{h,s,t} \\
&\quad + WOOD_{h,s,t}.
\end{aligned}$$

Fuelwood comes from dead wood (*deadwood*) in the forest and from wood cut during deforestation (*CUTREE* and *CUTREEG*). Wood collection is not restricted to one's own forest, meaning that everybody can collect wood in anybody's forest.

$$\begin{aligned}
&\sum_{h=1}^{H} \sum_{s=1}^{S} WOOD_{h,s,t} \le \sum_{h=1}^{H} \sum_{s=1}^{S} \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{p=1}^{P} \\
&\quad deadwood_a \cdot TREE_{h,s,o,a,y_4,t} \\
&\quad + \sum_{h=1}^{H} \sum_{s=1}^{S} \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{y=1}^{Y} \sum_{p=1}^{P} \\
&\quad (CUTREE_{h,s,o,a,y,p,t} \\
&\quad + (CUTREEG_{h,s,o,a,y,p,t}).
\end{aligned}$$

The closing tree volume is the opening stock adjusted for new planting (*NEWTREE*) less cutting (*CUTREE* and *CUTREEG*). *CUTREE* is the wood volume cut from the forest while *CUTREE*G is the wood volume cut from trees located in the pasture.

$$\begin{aligned}
&(1 + agrprt_{s,a}) \cdot TREE_{h,s,a,y-1,t-1} \\
&\quad + \sum_{p=1}^{P} (NEWTREE_{h,s,a,p,y,t}
\end{aligned}$$

$$
\begin{aligned}
&- CUTREE_{h,s,a,p,y,t} \\
&- CUTREEG_{h,s,a,p,y,t} \\
&- SELTREE_{h,s,a,p,y,t}) = TREE_{h,s,a,y,t}.
\end{aligned}
$$

Utility Function

The model maximizes total utility defined as the present value of utility over *T* periods.

$$TUTIL = \sum_{h=1}^{H} \sum_{s=1}^{S} \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^{t} \cdot UTIL_{h,s,t}.$$

Utility depends on net income and leisure. Income is the sum of crop and livestock sales adjusted for changes in livestock inventories and tree volume inventories and wages from seasonal migrants. Costs are the cash expenses for farm production and capital depreciation.

$$
\begin{aligned}
UTIL_{h,s,t} = {} & \sum_{c=1}^{C} \sum_{p=1}^{P} price_{c,p} \\
& \cdot SELCROP_{h,s,c,p,t} + \sum_{l=1}^{L} \sum_{p=1}^{P} price_{l} \\
& \cdot (SELLIV_{h,s,l,p,t} - NEWLIV_{h,s,l,p,t}) \\
& + \sum_{l=1}^{L} price_{l} \cdot (LIV_{h,s,l,t} - LIV_{h,s,l,t-1}) \\
& + pricemilk \cdot MILK_{h,s,t} \\
& + \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{p=1}^{P} \sum_{y=1}^{Y} price_{a,y} \\
& \cdot \Big(SELTREE_{h,s,o,a,y,p,t} \\
& - \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{p=1}^{P} pricenc_{a} \\
& \cdot NEWTREE_{h,s,o,a,p,t}\Big) \\
& + \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{y=1}^{Y} price_{a,y} \cdot (TREE_{h,s,o,a,y,t} \\
& - TREE_{h,s,o,a,y,t-1}) + \sum_{o=1}^{O} priceoffe \\
& \cdot yldcof_{a} \cdot TREE_{h,s,o,a_4,y_4,t} \\
& + \sum_{p=1}^{P} wage_{p} \cdot MIGRANT_{h,s,p,t} + \sum_{p=1}^{P} \\
& - \sum_{o=1}^{O} depirr \cdot IRRI_{h,s,o,t} - depmec \\
& \cdot MEC_{h,s,t} - CASH_{h,s,t} + \sum_{p=1}^{P} opport_{p} \\
& \cdot LEISURE_{h,s,p,t}.
\end{aligned}
$$

In the next equation the costs are aggregated.

$$
\begin{aligned}
& pricemirr \cdot \sum_{o=1}^{O} IRRI_{h,s,o,t} + \sum_{o=1}^{O} \sum_{p=1}^{P} priceirr \\
& \cdot NEWIRRI_{h,s,o,p,t} + \sum_{p=1}^{P} pricepur \\
& \cdot PURC_{h,s,p,t} + \sum_{c=1}^{C} \sum_{p=1}^{P} pricebuy \\
& \cdot BUY_{h,s,c,p,t} + priceker \cdot KEROSEN_{h,s,t} \\
& + pricemec \cdot \sum_{p=1}^{P} NEWMEC_{h,s,p,t} \\
& \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{d=1}^{D} pricenpk \cdot NPK_{h,s,o,c,d,t} \\
& + \sum_{o=1}^{O} \sum_{c=1}^{C} cost_{c} \cdot CROP_{h,s,o,c,t} \leq CASH_{h,s,t}.
\end{aligned}
$$

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