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# NATURAL RESOURCE MANAGEMENT IN THE HILLSIDES OF HONDURAS: BIOECONOMIC MODELING AT THE MICRO-WATERSHED LEVEL

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# ABSTRACT

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, we developed a bioeconomic model that combines dynamic linear programming with a biophysical model, then applied this model to a typical microwatershed. Over recent years, farmers from the selected microwatershed have followed a "vegetables-intensive" pathway of development. We ran different scenarios 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 paper help to test a number of induced innovation hypotheses. Many of our hypotheses are confirmed, but some of the model's results challenge conventional wisdom. The simulation results confirm 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 confirms that the relationship between population growth and natural resource condition has a U-shaped structure. In the long term, population pressure is likely to lead to continuing improvement in the condition of natural resources. The hypothesis that improvements in access to markets increase per capita incomes was confirmed by our results, but improvements in access to markets do not necessarily promote land conservation because land values do not necessarily increase. The hypothesis that agroecological conditions are the most important factors determining incomes and natural resource condition is confirmed 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 had the government banned inorganic fertilizer, undertaken a land reform, or promoted dairy production during 1975 to 1995, these policies would not have been successful. The forward looking baseline scenario suggests that erosion will continue to increase if prices remain constant. If commodity prices decline, however, erosion will decline 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.

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# NATURAL RESOURCE MANAGEMENT IN THE HILLSIDES OF HONDURAS: BIOECONOMIC MODELING AT THE MICRO-WATERSHED LEVEL[*]

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## 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 homogenous agro-ecological regions. An IFPRI study of the Central Hillside region of Honduras empirically identified five different pathways (Pender and Durón 1997), one of which corresponds to market-induced transitions to intensive vegetable cropping. This pathway was considered particularly interesting, because it illustrated the potential for commercial intensive agriculture in lands normally viewed as marginal.

The microwatershed of La Lima, located in the hillsides close to the capital, Tegucigalpa, was selected as a case study to better understand the causes and consequences associated with this type of transition and to generate hypotheses about possible policy

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actions in similar contexts (Bergeron et al. 1996). The study covered a period of 20 years (1975-1995) 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.

In this paper, we develop and use a bioeconomic model linking a linear programming and a biophysical model 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 provide indications as to 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; Hayami and Ruttan 1985). This theory explains investment and changing management systems in terms of changing micro-economic incentives for resource managers[1] (see Figure 1). Pressure factors (population, market demand and technological improvement) are assumed to induce changes in local market structure and prices, and in local institutions (labor arrangements, property rights). These changes in turn induce responses in natural resource management, both at the farm level (through changes in land use and adoption of new technologies) and at the community level (such as collective actions taken to regulate access to the resource base). The outcome of these changes is reflected in economic performances, natural resource conditions and social

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[1] See Scherr et al. 1997 for the theoretical framework; Pender 1996 for micro-economic detail.

well-being. The effects of external pressures upon productivity, incomes or the condition of natural resources vary depending upon local characteristics. These local characteristics combine with exogenous factors to determine the particular “pathway of development” adopted in each setting.

The modeling described in this paper is meant to simulate the aggregate behavior of farmers in the La Lima microwatershed. Based on our conceptual framework, the following five hypotheses are postulated about the dynamics in natural resource management in the hillsides. The model will help to test each hypothesis.

- Population pressure leads to greater total income but to 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.[2]
- 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 have an ambiguous effect on natural resources.
- Agroecological conditions are the most important factors determining incomes and resource conditions.

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

## 2. AGRICULTURE IN HONDURAS

Honduras is one of the poorest countries of the American continent with a GDP of $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 1996). Eighty-five percent of the landmass is under slopes greater than 12 percent, and the spatial distribution of land is as follows: 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 in 10 to 25 percent of the hillsides of the region (Olderman, Hakkeling, and Sombroek 1990), and that erosion ranks between nine and 50 metric tons per hectare per year on slopes of 15 to 40 percent (Wouters 1980). Various sustainable cultivation techniques have been developed for such environments, but their adoption is low in Honduras (Bunch and Lopez 1995; Pender and Durón 1996).

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 sector to the detriment of agriculture. Beginning in the early 80s, 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, namely: 1) the extensification of maize production; 2) the intensification of vegetable production; 3) the increase of 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.

## 3. THE MICROWATERSHED OF LA LIMA

We collected data in the microwatershed of La Lima from January 1995 to October 1997.[3] Data collection included:

1) A household census detailing land, labor, capital, livestock, trees, access to water, on-farm and off-farm activities (Bergeron et al. 1996);
2) twenty in-depth interviews of households, to determine incomes, expenditures, consumption, and investment. Crop and livestock budgets were also established;
3) aerial photographs of the microwatershed from 1955, 1975 and 1995 were analyzed to determine current and past land use patterns in the microwatershed (Bergeron and Scherr 1996). The aerial photographs were digitized and introduced into a GIS software to analyze spatial patterns in land use, soils and topography;
4) a history of plot and farm changes over the last 20 years was undertaken based on

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[3] Data collection was a collaborative effort between the Escuela Agrícola Panamericana of Zamorano, IICA and IFPRI.

recall interviews with farmers (Bergeron and Pender 1996);[4]

5) price time series were collected and information on the evolution of the market structure was elicited from key informants (Mendoza 1996); and

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

## GENERAL CHARACTERISTICS

The microwatershed of La Lima covers approximately 10 square kilometers. Only 18 percent of the microwatershed has land with less than 15 percent slopes; 52 percent has over 30 percent slopes. The microwatershed is typical of the hillsides of Central America with respect to its soils, altitude (1000 to 1800 meters), and climate (bimodal rainy season with mean yearly rainfall of 1200 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 with 25 percent of the area, followed by pastures with 21 percent, and mixed pastures and trees with 20 percent. Fallows occupy 17 percent and the permanently cultivated area 14 percent. This land use has not changed much over the past 20 years. Pastures have remained almost constant because large owners prefer large ranching over cultivation. Forests, mainly located on steep slopes, also remained largely unaltered. The main change over the last two decades has been the development of

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

intensive irrigated cultivation of vegetables; but the area affected has remained relatively small.

In 1995, the microwatershed supported 507 inhabitants living on 80 farms. Over the last 20 years, this population has 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 to the Honduran average of 26 rural inhabitants per square kilometer.

The average cash income in 1995 among a sample of 20 farmers was \$800 per worker[5] and the average daily income was higher than the official daily minimum wage of \$1.20[6]. However, income variations were important: only 30 percent of the workers earned more than the community's average, while 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, and 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 do not work in agriculture, the average consumer/producer ratio is only 0.3. Extended families with several married adults within the household are rare but collaboration

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

[6] 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.

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 with an average of 40 days per farm per year. Wage labor is the primary source of income for 25 percent of the workers, and 8 percent of the workers earn wages as a secondary activity. Temporary out-migration is rare, probably because demand for labor is high in the microwatershed.

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.

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 percent 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 small. 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, while ranchers have larger fields of maize for sale that are share cropped 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 farmers now (illegally) tap for their production needs. Pesticide and inorganic fertilizer use has increased rapidly with vegetable cropping, but analysis by the Panamerican Agricultural School of Zamorano found no trace of contamination in the water or soils of La Lima (personal communication).

### *Livestock Production*

Cattle ranching is relatively important in La Lima. In 1995, there were 486 head of cattle, or one head of cattle per person. This is similar to the Honduran average (FAO 1997). Cattle density is high at 0.6 animal 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 water-logged flat areas. Some areas were found to be overgrazed, but 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 at different locations within the microwatershed to assess existing and future water shortages. For that purpose we used a flow meter (Tamashiro and B. Barbier 1996). In April 1996, at the end of the dry season, the springs of the microwatershed produced 869 liters per minute. Of this amount 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. Ten 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 already have had to reduce their production drastically due 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 Corporation Hondurena de Desarollo Forestal, a government agency which took away cutting permits from local farmers. Second, most of the remaining forest 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 by taking *de facto* control of large areas of forested land, even though they do not officially own them. 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 (Canales 1996) and part of the Ojojona soil series (Simons 1977) that is common in Honduras. Forty nine percent of 243 soil samples selected randomly were classified as loamy clay, which are soils with more than 28 percent clay content (Eriksen 1996). The clay content and the kaolinite nature of this soil makes for poor drainage. Because they are water logged when it rains, and compact after a few days without rain, these soils are difficult to plow. Farmers in La Lima classify their soils according to texture and fertility (Ardón 1995), but they do not consider soil characteristics as important factors for crop choice, because they see them as relatively homogenous throughout the microwatershed.

The soils are acid with a pH of about 5 (Eriksen 1996). The soil analysis, compared to 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 and nitrogen deficiencies.

Soil fertility management has changed in La Lima over time. 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. In 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*

We measured erosion in one representative maize plot using the "nails and washer" technique (Burpee 1997) during the rainy season of 1996. Erosion was measured at 4 millimeters in a 160-meter-long maize plot with a slope averaging 25 percent. With a soil density of 1.4, this translates into an erosion rate of approximately 56 tons per hectare, which is about normal given the characteristics of this plot. We also measured sedimentation at the outskirts of the microwatershed during the rainy season of 1996. A rough extrapolation of the sedimentation observed suggests an erosion level of 6 tons per hectare for 1995 for the entire microwatershed[7] (crop, pasture and forest included). Six tons of eroded soil per hectare 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 with the lack of rain and water logging of the soil than with erosion. There is evidence that farmers even prefer to plant maize on slopes. Twenty-nine percent of the maize area is planted on slopes greater than 30 percent, while 34 percent of the total maize area is planted on slopes between 15 and 30 percent. Only 36 percent is planted in areas with less than a 15-percent slope. This situation does not seem to be due to limited access to flat

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[7] These numbers should be taken with caution because soil erosion is an irregular process that occurs during a few rain events during the year.

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.[8] The main methods used are stonewalls, found in 15 percent of the plots, and contour plowing, found in 14 percent of the 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 (the eroded soil accumulates behind these fences or at the lower end of the fields creating in the long term a relatively terraced landscape which characterizes the microwatershed today); and 3) plots are small and running water 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.

## 4. MODELING METHOD

Linear programing has been widely used to predict supply response and farmers' incomes under different agricultural policy scenarios (Hazell and Norton 1985). More recently, a new type of model called a bioeconomic model, has been developed. A bioeconomic model links mathematical programming formulations of farmers' resource

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[8] For a review on soil conservation experiences in Central America, see Lutz et al. 1994 and Sims and Elli-Jones 1994. For a review on agroforestry in Central America, see Current, Lutz, and Scherr 1996.

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 while 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 in developed countries. First, farming systems of 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 1979; Beets 1989). Second, most farming systems in developing countries include livestock and tree management. Modeling these activities requires 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 condition results from complex biophysical processes which are difficult to quantify. Fourth, land degradation, such as erosion and soil mining, is more critical in developing countries for ecological and social reasons. 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; G. Kruseman et al. 1995; B. Barbier 1995). 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 et al. 1996; B. Barbier and Benoit-Cattin 1997). Finally, rapid changes in population and markets in developing countries limit the value of static analysis.

In response to these challenges, the model presented below is both dynamic (with a five-year planning horizon) and recursive (over the 45-year period 1975 to 2020). We designed the model at the microwatershed level[9] and included two social groups, ranchers and small farmers, who interact through a labor market. The model includes soil erosion and interactions among livestock, crops and forest. Yields and erosion parameters are given by the biophysical model EPIC (Erosion Productivity Impact Calculator) developed by Williams, Jones, and Dyke (1987).

## THE LINEAR PROGRAMMING MODEL

The model maximizes the aggregate utility of the whole microwatershed over a five-year planning horizon.[10] Utility is defined as the discounted value of future net monetary incomes plus the closing value of livestock, plus the value of leisure taken. We assumed a 15-percent discount rate in the baseline scenario. A sensitivity analysis showed that changes in the discount rate had a moderate effect on land use.

Although the model is dynamic and optimizes over a five-year planning horizon, we also solve it recursively each year to generate a series of annually updated plans. This is done 20 times for the period 1975 to 1995 and 25 times for the period 1995 to 2020. In this framework, the optimal solution for the first year of the planning horizon becomes the initial

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

[10] The program is written in GAMS (Brooke, Kendrick, and Meeraux 1988).

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. The key assumptions of the modeling process are described in the following section (a full description is found in Appendix 1):

### *Population and Labor*

Birth and mortality rates are treated as exogenous to the model. However, population density remains endogenous because outmigration flows change the size of the population according to the opportunity cost of migration. Farmers can hire or sell labor, which is paid daily at the official wage. There are two off-watershed activities: 1) the ranchers have off-watershed activities with higher returns because of their mostly urban location, and 2) small farmers have off-watershed activities that consist mostly of low-wage activities because of their rural location.

### *The Division of the Microwatershed*

The simulated microwatershed is delineated into three sectors based on altitude. The objective of the disaggregation is to assess the effect of water use by one sector upon the sector located below. Springs are used for human, livestock and crop consumption. The unused water runs out of the microwatershed. The first sector which is located above 1500 meters benefits from a limited amount of water during the dry season and is controlled by a few ranchers. The sector located between 1350 and 1500 meters has an irregular topography, but benefits from several abundant springs during the dry season. The lowest sector, between 1100 and 1350, is flatter and benefits from good access to the main stream of the microwatershed.

Each sector has a different initial endowment of three types of soils with varying slopes, soil depths and productivity. Each sector is managed by two groups of farmers, the small farmers and the ranchers with different initial population densities. Three sectors, three types of soils 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 sector is located at a different distance from the main road and from one another, giving rise to varying transportation costs in terms of time from sector to sector.

### *Crop Production*

The model allows for a choice between four crops: maize, potatoes, onion and 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. We distinguish 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 linearsegmented approximations of non-linear functions.[11] The production functions are specified for each type of crop, each sector, 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, plus the effect of the amount of organic and inorganic fertilizers used, plus the effect of plowing instead of hoeing, minus the effect of inadequate irrigation during the dry season, minus the effect of soil erosion, minus the effect of insufficient soil depth. The effects are non-linear and are approximated by linear segments. An exogenous parameter which 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

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

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 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 plowing, mules for transportation, and cattle for producing milk, which is sold in some scenarios or else is consumed on the farm.

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 available to the plant. We will call this loss the "nutrient effect." Second, erosion reduces yields by diminishing soil depth, which reduces root growth once a minimum soil depth is reached. We will call this loss the "soil depth effect." We modeled these two processes in the linear programming model based on the data generated by EPIC. 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 while 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 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 decreases 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. We add an equation 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. The model does take into account externalities.

### *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 (from 1 to 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. We run several scenarios where wood can be sold and has a stock value. Coffee trees are assumed to start to producing coffee beans three years after planting. The model can plant two varieties of coffee, a traditional 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. To estimate erosion levels, we selected the Modified Universal Soil Loss Equation (MUSLE) adapted for small microwatersheds (J. R. Williams, Jones, and Dyke 1987).

### *Results*

EPIC was parameterized to the soil conditions, climate and cropping pattern found in La Lima. We modeled yields of maize, onion, potatoes and tomatoes grown in different rotations. In each scenario we kept the same climatic sequence, in order to compare different scenarios. Yields used in the LP model are the average of the yields obtained from 12 years simulations with EPIC. We adjusted the agronomic characteristics of the maize included in EPIC 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, we compared the erosion and non-erosion scenarios for three different types of slopes and fertilizer practices. The results for maize and potatoes planted in a deep soil (30 centimeters) are reported in Tables 1 and 2. These simulations confirm that use of fertilizers increases soil cover which reduces erosion.

We 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 1 and 2. When soil depth becomes insufficient, yield decline is significant. The results from the EPIC simulations are incorporated into the economic model.

**Table 1 Simulated effects of soil erosion and fertilizer practices on maize yields on three different slopes (tons/ha)**

| Erosion / Fertilizer Use | Slope | | |
|---|---|---|---|
| | 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 in t/ha | 12.98 | 59.48 | 171.0 |
| Yields with no erosion and NPK = 100 kgs | 2.135 | 2.134 | 2.130 |
| Yields with erosion and NPK = 100 kgs | 2.127 | 2.103 | 2.043 |
| Erosion in t/ha | 7.7 | 34.32 | 93.59 |
| Yields with no erosion and NPK = 300 kgs | 2.887 | 2.874 | 2.848 |
| Yields with erosion and NPK = 300 kgs | 2.880 | 2.864 | 2.811 |
| Erosion t/ha | 4.65 | 14.32 | 44.9 |

**Table 2 Simulated effects of soil erosion and fertilizer practices on potato yields on three different slopes (tons/ha)**

| Erosion / Fertilizer Use | Slope | | |
|---|---|---|---|
| | 10% | 22% | 35% |
| Yields with no erosion, NPK = 500 kgs | 14.364 | 14.320 | 14.215 |
| Yields with erosion and NPK = 500 kgs | 14.060 | 13.440 | 13.130 |
| Erosion (t/ha) | 39 | 163 | 612 |
| Yields with no erosion and NPK = 700 kgs | 16.446 | 16.390 | 16.272 |
| Yields with erosion and NPK = 700 kgs | 16.215 | 15.720 | 15.156 |
| Erosion (t/ha) | 28 | 123 | 451 |

# 5. MODEL SIMULATION RESULTS

The primary purposes of constructing the model were to test 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 report on the baseline results for 1975 to 1995 and validate these results against the actual history of the La Lima microwatershed over this period.

## BASELINE SCENARIO

In the baseline scenario, we compared the land use generated by the model with the historical information obtained from farmer interviews in La Lima. The result of this comparison allows us to establish the validity of the model and its ability to correctly replicate the decisions taken by farmers in the community. We particularly 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: 1) the diffusion of sprinkler irrigation in 1979; 2) the construction of an all-weather road in 1985; 3) its improvement in 1993; and 4) the construction of a water distribution system in 1992. Changes in historical prices were also fed into the model, as they were determined exogenously (Figure 2). Prices had been under strict government control until 1989, but this changed dramatically after the structural adjustment program of 1990.

### *Land Use*

The simulated land use shows an evolution that is similar to the evolution recalled by farmers in the plot history survey (Figures 3 and 4). 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.

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 need to cut trees 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 we extend the planning horizon in the model, but not enough to compete with vegetables given the current price conditions in La Lima.

Figure 5 shows the simulated land use by slope category. It shows that soils with less than 15 percent slopes are predominantly in pastures. This is because water logging on flatter fields results in lower yields than soils with a steeper slope. The 15- to 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 6 shows the simulated land use for three different zones of the micro-watershed. The upper zone has the largest proportion of crops and pastures while the two lower sectors still have extensive forests.

Figure 7 shows the simulated land use for each group of farmers. Small farmers have more than the half of their holding under crops with a decreasing area of forest over time, while 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 in 1990; and second, a period of dramatic increase after market liberalization (Figure 8)[12]. The increase during the first period is due to technological improvements, which allow incomes to augment slightly despite worsening prices and continued population growth. After 1990, however, simulated real

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[12] All costs and incomes are deflated to 1987 prices with the Consumer Price Index (World Bank 1996) and are measured in lempira (in 1987, one lempira was equal to US$ 0.3).

income doubles in less than four years because of rapidly increasing prices for vegetables.

There were sizeable differences in the results for different types of farmers (Figure 9). 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 10)[13]. Incomes from livestock decrease while maize is replaced by onions and potatoes as the first source of income. Coffee and off-farm activities remain 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 11) and increasing application of fertilizers (Figures 12 and 13).[14]

The simulated yields for 1995 are close to the actual yields farmers obtained in La Lima. Surprisingly, however, the recent crop price increases does not result in large increases in yields. This is explained in the model by the limited availability of labor at

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

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

harvest time.[15] The model prefers corralling (where cattle graze maize residues) (Figure 12) to compost or manure production because of the high labor requirement.

### *Commercialization*

The sale of part of production increases with time, particularly after the adoption of irrigation and fertilization techniques in 1979-1980, and after the construction of the road in 1985 and its improvement in 1993 (Figure 14). When irrigation is adopted in 1979, the model begins selling less maize, 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. We will explore the reasons for this 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 15). 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.

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[15] Note that we did not allow for immigration in the model, 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.

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, freeing 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 16). 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 sector 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 6700 tons per year (or 7 tons per hectare per year) (Figure 17). This number is almost the same as that which we estimated in 1996 at the out-stream of the microwatershed.[16] To obtain this result, however, we had to suppress the "nutrient effect" of erosion on yields in the model. If the nutrient runoff effect is maintained, then the simulated erosion becomes less than 3 tons per hectare as the model adopts grass strips on 40 hectares at the beginning of the simulation. This technique was adopted because it reduced erosion while requiring

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[16] 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 sediments 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.

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 were deep enough (less than 3 percent yield loss per year on steep slopes). Moreover, incomes only increase by 1.2 percent in the model after we removed 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. In consequence, we removed the "nutrient effect" of erosion in the baseline scenario to mimic farmers' perceptions. However, we maintain the erosion calculation and the "soil depth effect" on yields.

In the baseline scenario, soil depth diminishes rapidly on the steeper slopes (Figure 18) and quickly reaches the level where roots become affected. The model reacts by abandoning these plots and reclaiming new ones, this approach being 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 19). The model does this as the critical soil depth becomes insufficient, and there are no more pastures or forest lands available for cropping. These results correspond to reality, and this land unit is today 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 20). As a result of the introduction of sprinklers into the model in 1979, water outflows from the microwatershed decreased significantly. Figure 20 shows that in the upper microwatershed, the small amount of spring water is rapidly used for irrigation. After the potable water distribution was introduced in 1993, the model used even more water because the distribution system allowed the irrigable area to be extended.[17]

### *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.[18] 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 21). This result is due to the increasing profitability of labor intensive activities such as vegetable production. Consequently, farmers have fewer reasons

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[17] We add a lower bound in the model for the stream volume, because in reality there is an implicit rule that users cannot completely dry a stream.

[18] 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.

to acquire new land. Land is still abundant in La Lima and extra land would increase the current income 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 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 productivity incomes.

The shadow prices of labor vary by period, and are not uniform through time or season (Figure 22). 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 smooths 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 technique of "dobla"[19] of 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 22). The limiting period becomes the middle of the rainy season, when the maize harvest competes with vegetable harvesting and potato planting.

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[19] 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.

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 23). 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 years of the simulation because water becomes a scarce resource when the installation of the water distribution system allows an increase in irrigation (Figure 24). Water then becomes a binding constraint on expanding the irrigated area but the model reacts by producing vegetables during the rainy season.

## HYPOTHESES TESTING

In this section, we use model simulations over the period 1975 to 1995 to test the induced innovation hypotheses formulated in section 1 about the effects of population pressure, increased market access, improved technologies and market prices, and the impact of agroecological conditions on these relationships.

### *The Effect of Population Pressure*

Our first hypothesis in section 1 states that a) 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. To test this hypothesis, we run two contrasting scenarios: one with increased population pressure, and another in which no population growth is assumed.

To simulate population growth, a high level of in-migration was allowed in the model.[20] The results show that population increases rapidly before stabilizing at 150 inhabitants per square kilometer, 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 25). All the forest is cut and households have to turn to alternative energy sources (e.g., kerosene for cooking). Most cattle are also sold, while 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 26).

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 25). Soil erosion is also halved (Figure 26).

The results of the two population simulations confirm our initial hypothesis that when population density is still relatively low, population pressure has negative effects on natural resources. However, when the population reaches higher density and when 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

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[20] This scenario only has a theoretical purpose because it is not likely that in-migration will occur in Central Honduras, since all the land is already individually allocated.

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, 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, we should expect that any future expansion of crops will occur at the expense of pastures, and that the forest area will remain largely intact.

The simulations also show 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, while 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 Market*

Our hypothesis is that market access increases incomes and reduces erosion because land values increase. To test this hypothesis we ran two scenarios to simulate the effect of market access, using distance to a road as an indicator of market access.

In the first simulation, we remove the equations capturing the effect of the construction and subsequent improvement of the road in the community. The model responds by transporting products to the next community 6 kilometers away. However, some of the more perishable crops (like 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 27). The model still produces a similar amount of maize, onions and potatoes as 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 28 shows that the road construction leads to a sharp increase in soil erosion, and this is because farmers start to produce more potatoes for the market, which are a highly erodible crop.

We also simulated different scenarios with respect to the distance of the microwatershed from the main road. Specifically, we simulated distances of 20, 30 and 40 kilometers from the village to the main road, and also a scenario where the distance remains unchanged, but where the connecting road is removed. All transportation must be made by mule. This simulated situation of remote market access (which is actually quite typical in the Central Region), has a radical effect on per capita incomes (Figure 27). Coffee production increases sharply in the simulation after the coffee price boom of 1979, while 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 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 28). 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 production 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. In our initial hypothesis we were expecting 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*

Our third hypothesis states that technological innovation compensates for decreasing returns to labor. To test this hypothesis, we simulate removal of two key technologies from La Lima, namely crop variety improvement, and sprinkler irrigation.

*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 29).

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 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 30).

*Irrigation in 1979.* Sprinklers were introduced by the extension services in 1979. If we eliminate this technology, 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 29).

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 30). 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 than a previously eroded community because they still have deep soils thanks to better soil management.

*Potable Water Distribution in 1993.* When we simulate removal of the potable water distribution system in 1993, there is a slight income decline of about 2.5 percent (Figure 29).

The water distribution system has a smaller than expected impact on incomes, because it was simply not designed for irrigation. In reality, however, the potable water discribution system has a larger impact on equity because it allows almost every farmer to produce at least a few square meters of vegetables near their house during the dry season, while before, only farmers with plots near the main streams could produce them. The potable water distribution system has no effect on erosion.

*Conclusions*. Seed improvement had a very 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, we found a difference in the varieties used by rich and poor farmers in La Lima, with the poor using inferior varieties. 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.

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 those areas closest to streams and water points. The 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 increased erosion because it increased rainy season potato cultivation. Adoption of sprinklers first reduces erosion by reducing the area of rainy season crops, but irrigation, by increasing labor cost during the dry season, makes investment in land conservation less likely.

### *The Effect of Agro-Ecological Conditions*

Our hypothesis is that agro-ecological conditions are the most important factor determining incomes and erosion. To test this hypothesis, we ran three simulations. 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 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 31). 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 32).

*No Vegetables*. If vegetables cannot be produced at all in the microwatershed, income would fall to 30 percent below the baseline in 1995 (Figure 31). 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 32).

*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 32). 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 31).

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.

*Conclusion about Agro-Ecological 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 constructed, incomes decrease to very low levels.

## POLICY INTERVENTIONS

The bioeconomic model provides a tool for simulating what the impact of alternative policy interventions might have been on incomes and natural resource conditions. The policy scenarios simulated below were selected because of their relevance to ongoing policy discussions in Honduras. In each case, we simulate what the impact would have been during the period 1975 to 1995. First, we simulate what would have happened if the liberalization of 1990 had not occurred. Second, we simulate whether a ban on inorganic fertilizers over the period 1975 to 1995 would have made organic agriculture a viable alternative. Then we simulate a land reform, to forecast how this would have impacted on the development of the community. Finally, we run one scenario to see whether dairy markets would have developed in La Lima if there had been access to a processing plant.

### *Market Liberalization*

We examine the impact of market liberalization by "canceling" this policy in 1990, and keeping prices at their 1990 level thereafter. In the first three years after 1990, the scenario without liberalization produces higher incomes because prices were more favorable to agriculture. However, by 1995, incomes without liberalization are 32 percent lower compared to the baseline scenario (Figure 33) 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 reduced soil erosion slightly (Figure 34).

### *No Inorganic Fertilizer*

In this scenario we simulate what would have happened during 1975 to 1995 if the use of inorganic fertilizer had been prohibited. This possibility is currently being discussed in Honduras, where there is a strong movement to promote organic agriculture 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 to the baseline scenario (Figure 35). 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 residues, which in turn reduce livestock feed and livestock manure. The model also brings more land under cultivation to compensate for loss in yields. Furthermore, lower fertilization decreases soil cover by crops. These changes lead to a 20-percent increase in soil erosion by 1995 compared to the baseline scenario (Figure 36).

### *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. Under this scenario, a portion of the population in the more highly populated areas moves to the less populated area. Also, the population resettles to take full advantage 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 37). 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 more erosion because a larger area is cultivated (Figure 38).

### *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 1985 when the road is built, to become one of the main production activities. It also significantly increases per capita income (Figure 39). 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 endowment fosters 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 considerably, farmers growing only irrigated onions during the dry season. This new land use produces very low levels of erosion (Figure 40). However, in 1993 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 a ban on inorganic fertilizer, a land reform, and the development of dairy production would not have been successful.  This is because intensive vegetable production requires chemical fertilizers, while providing an important income earning opportunity for small farms.  Moreover, vegetable production is more profitable than dairy production.

## FORWARD LOOKING SCENARIOS

In this section, we analyze four scenarios for the future.  We begin with a baseline scenario extending over 100 years, from 1975 to 2075.  Key assumptions are a) population increases at 3 percent per year, b)  and 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, we then run three scenarios corresponding to different price assumptions.  These simulations cover the period 1995 to 2015.

### *Forward-Looking Baseline Scenario*

The baseline scenario is run to assess the effect of erosion over the very long term. Figure 41 shows how growing population pressure will lead to greater cultivation. If relative prices remain constant, large ranchers located in the upper, less irrigated part 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.

Soil erosion remains relatively constant (Figure 42) until the steeper slopes are cultivated creating dramatic erosion that depletes the soils. However, by 2060 erosion decreases to less than one ton per hectare, thanks to the construction of conservation structures (Figure 43); 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 44). 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.

### *Scenario with Decreasing Vegetable Prices*

Current high prices of vegetables are probably a short-term reaction to recent policy changes, such as the devaluation of the local currency, the end of price controls and the opening of the border to neighboring countries. As more communities increase vegetable production, prices are likely to fall to lower levels Thus, we simulate a scenario where vegetable prices decline continuously at a rate of 3 percent per year over the next 25 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 due 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 45). 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 46).

### *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 2050 plummet to 56 percent lower than in the baseline scenarios (Figure 45). 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 46).

### *Scenario with Increasing Inorganic Fertilizer Prices*

Increases in the price of inorganic fertilizers are plausible as the world supply of nonrenewable nutrients, such as potash and phosphates, are becoming scarcer. An increase in fertilizer prices by 3 percent per year reduces per capita incomes but has a much lower effect than a decrease in crop prices (Figure 45). Erosion is slightly higher in this scenario because the model applies less fertilizer and expands the crop area (Figure 46). 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 fertilizers in determining their level of incomes. 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). However, 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.

## 6. GENERAL CONCLUSIONS

The results of the bioeconomic model presented in this paper helped to test a number of induced innovation hypotheses. Many of our initial hypotheses were confirmed, but some of the empirical results challenged our expectations.

The simulation results for scenarios with differing assumptions about population growth confirmed 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 changes in market prices, 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 last 20 years were the switch to improved maize varieties, the adoption of irrigation and fertilization technologies, and a favorable market situation for horticulturals.

Our second hypothesis relates to the effects of population increases on natural resources condition. The model tested whether the hypothesis of a U-shaped function[21] held up in La Lima. The simulations indeed found a relationship of this type, but only after almost tripling the population level in the micro-watershed, a condition that is unlikely to

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

occur any time soon in La Lima. However, there is very little evidence of a U-shaped relationship to date in La Lima. There are two reasons for this: first, population increases had relatively small effects on increasing the cropped area, due to the intensification of production -- resources tended to be concentrated in a relatively small area. True, we noted signs of increasing environmental deterioration in La Lima, but these were mainly found in horticultural plots during the rainy season -- said otherwise, recent environmental problems were due more to the development of vegetable production than to population growth. Second, farmers did not react to increased degradation by making land investments, as we expected they would. It seems that farmers did not feel the need to improve their practices, so 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 hypothesis that improved access to markets would increase per capita incomes was confirmed by our results. Following the opening of the road and greater access to regional markets, local farmers undertook a series of structural transformations that enabled them to benefit from the advantageous prices offered by non-traditional 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.

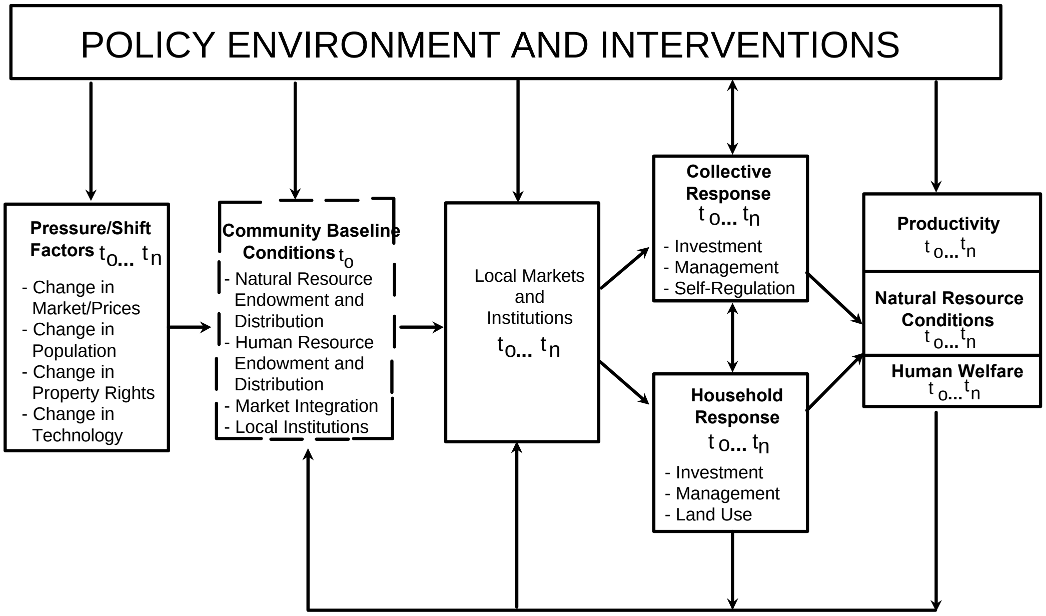
The second part of that hypothesis, which associates market access with land investments, was not verified. Improved access to markets does not necessarily promote land conservation because the value of land does not necessarily increase with greater market access. This is well illustrated in our model 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 make labor-intensive land investments less likely. Understated here is the fact that economic incentives are not sufficient; environmental ones also have to be present. In La Lima, as we 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 we should expect investments to happen.

The last hypothesis, which stated that agroecological conditions are the most important factors determining incomes and natural resource condition, is also confirmed by the results. Our simulations demonstrate that incomes would be much lower, and degradation much higher, if vegetable production had not been possible. Farmers would have been reduced to the adoption of 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, among which the agroecology plays a fundamental role. In other words, notwithstanding the economic advantages of horticultural production, this strategy is not suited for 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 us a good example of this. This community clearly benefitted 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 we documented in this paper. Note, however, that the simulations also suggested that, keeping all else constant, alternative policies which 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. Thus, it emphasizes the importance of recognizing the diversity of complex production environments and their implications for understanding the differential impact some policies will have 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.

Figure 1--Conceptual framework



Source: Scherr et al. 1996

**Figure 2: Deflated prices of the main products**

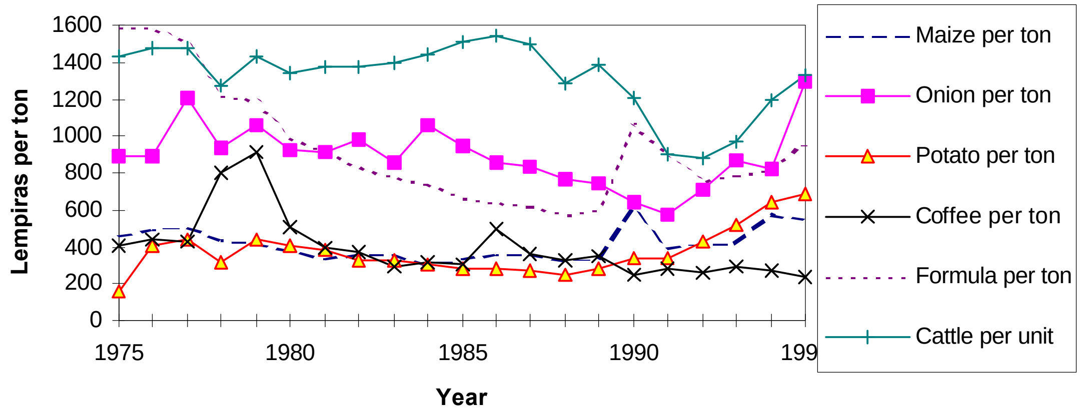


**Figure 3: Simulated land use**

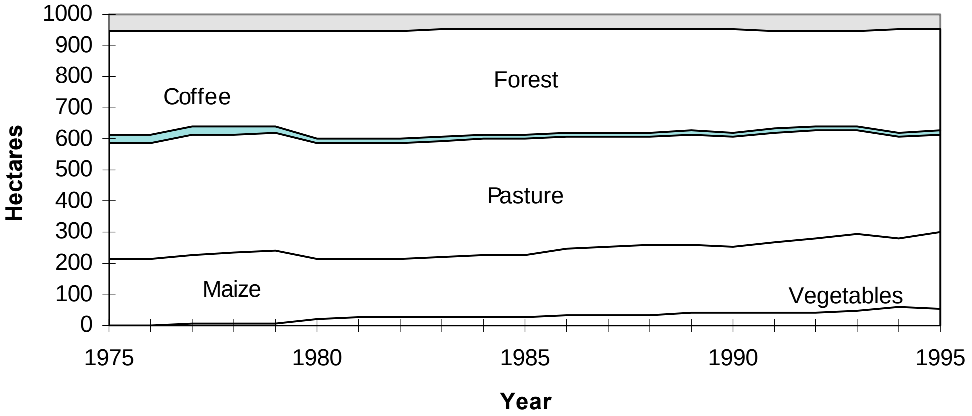
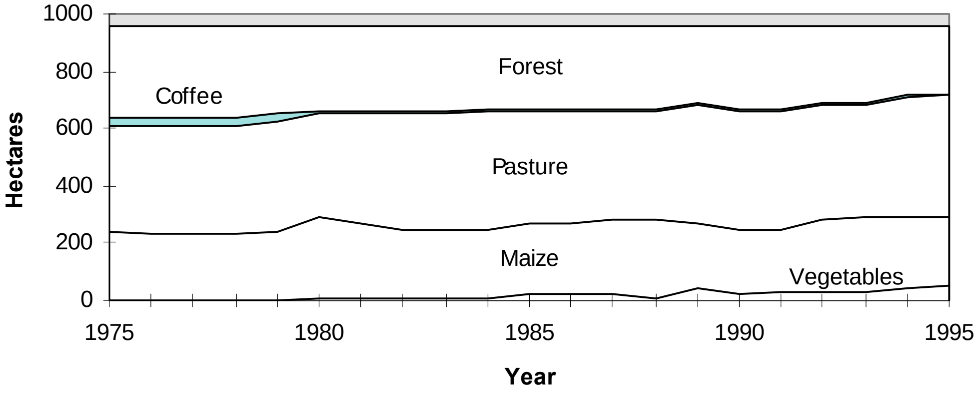


**Figure 4: Historical land use**



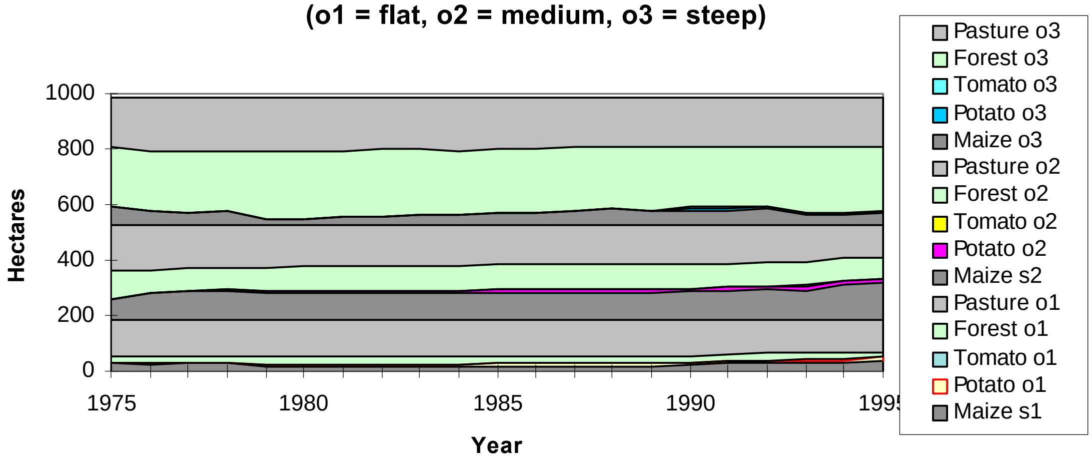


Figure 5: Simulated land use by slope (o1 = flat, o2 = medium, o3 = steep)

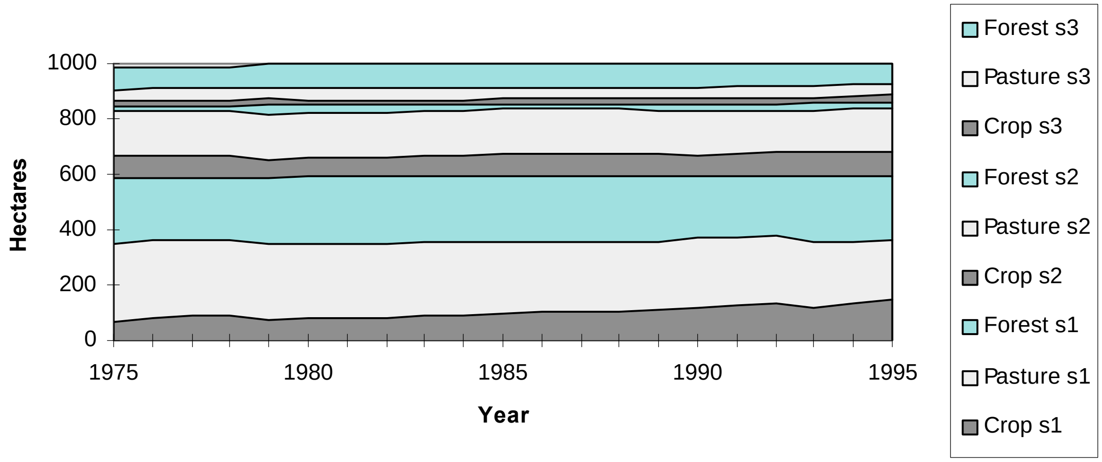


Figure 6: Simulated land use by sector (s1 = top, s2 = medium, s3 = lowest)

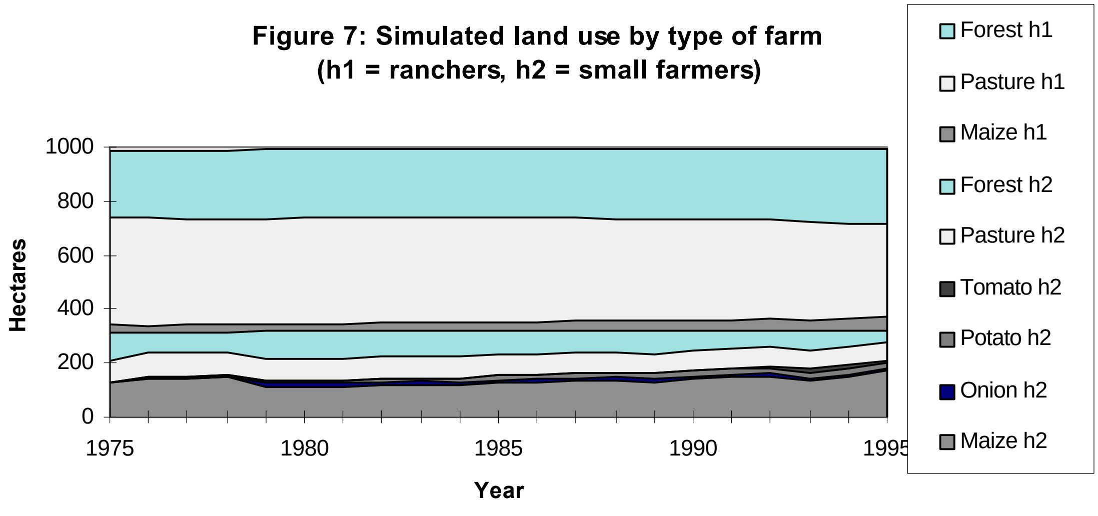


Figure 7: Simulated land use by type of farm (h1 = ranchers, h2 = small farmers)

Figure 8: Simulated income per person

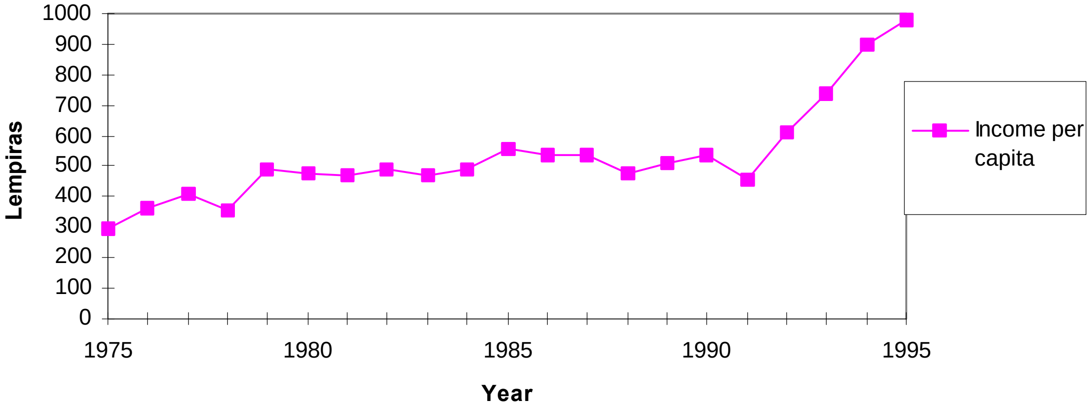


Figure 9: Simulated income per person by group of farmer and sector (s1 = top sector, s2 = medium sector, s3 = lowest sector)

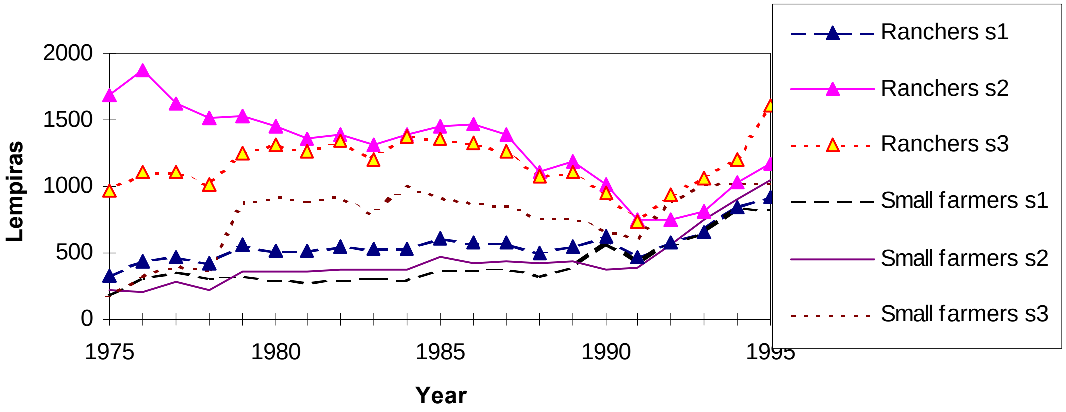


Figure 10: Simulated sources of income in the whole microwatershed

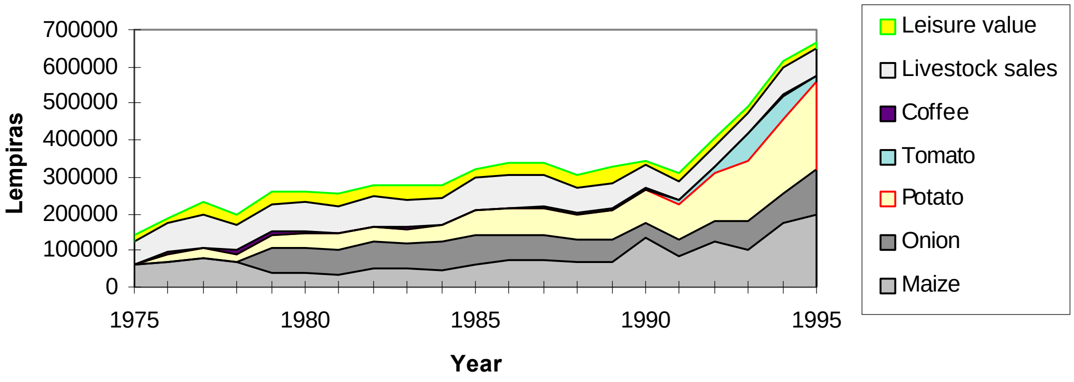


**Figure 11: Simulated yields**

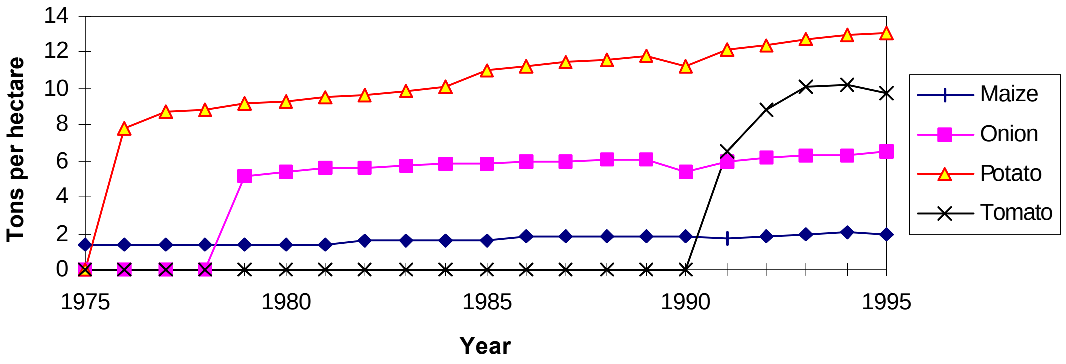


**Figure 12: Simulated use of fertilizers**

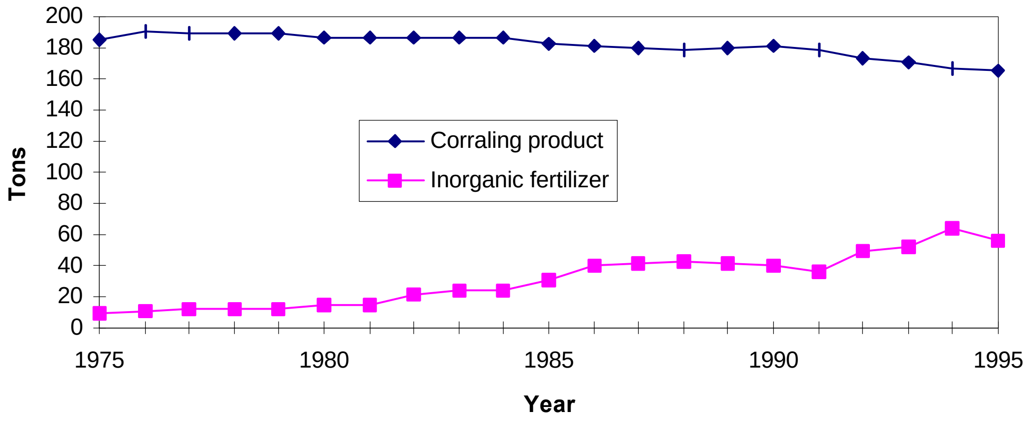


**Figure 13: Simulated inorganic fertilizer use per hectare**

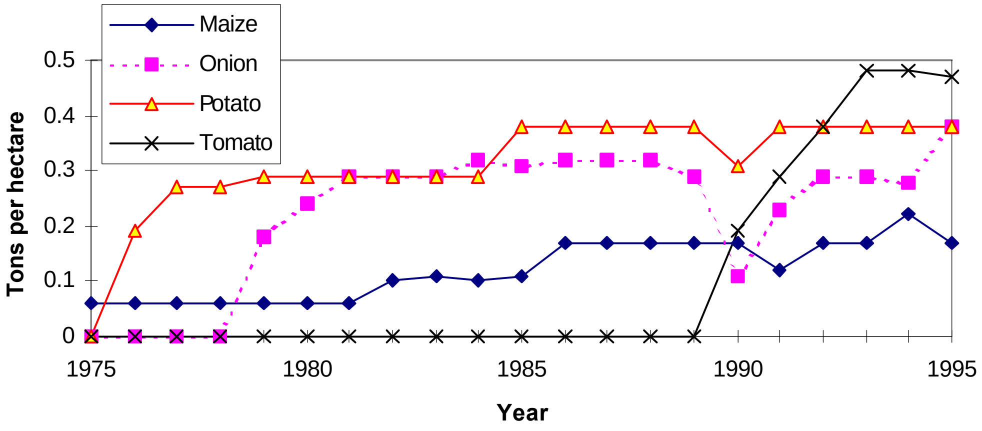


Figure 14: Simulated use of crop production

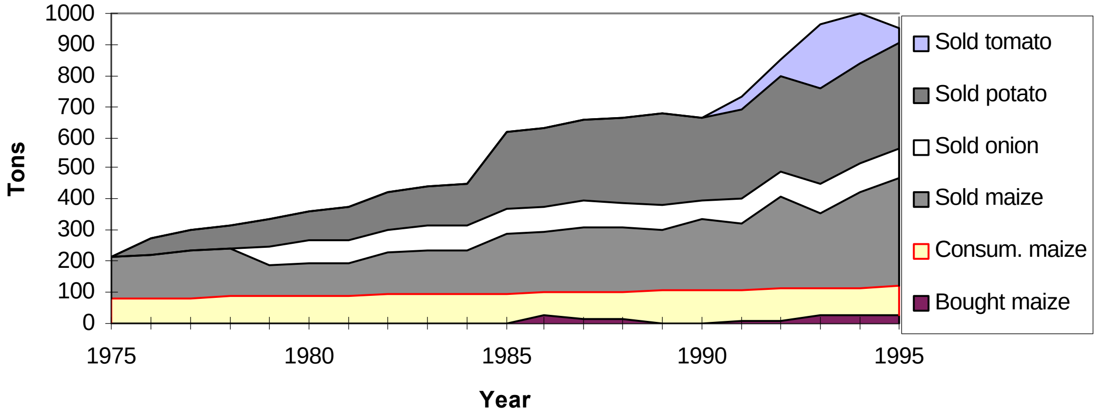


Figure 15: Simulated livestock herd size

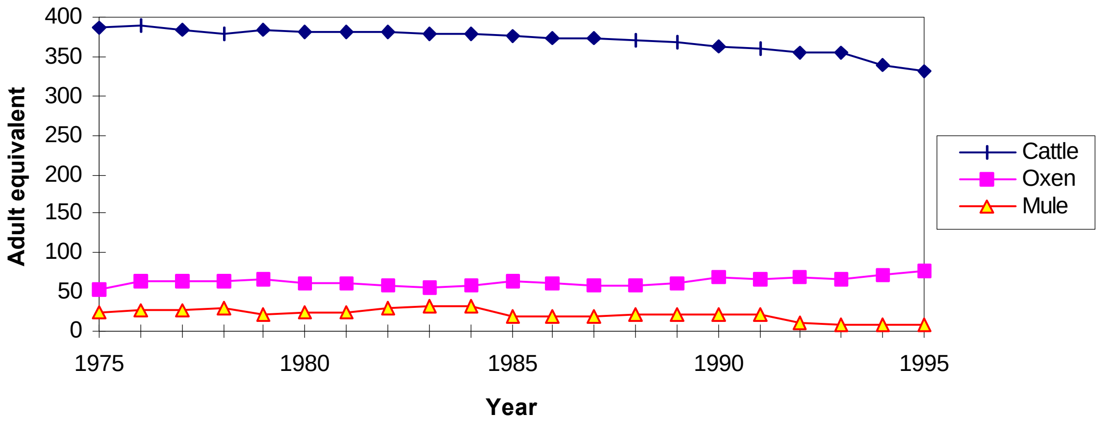


Figure 16: Simulated transportation by mule

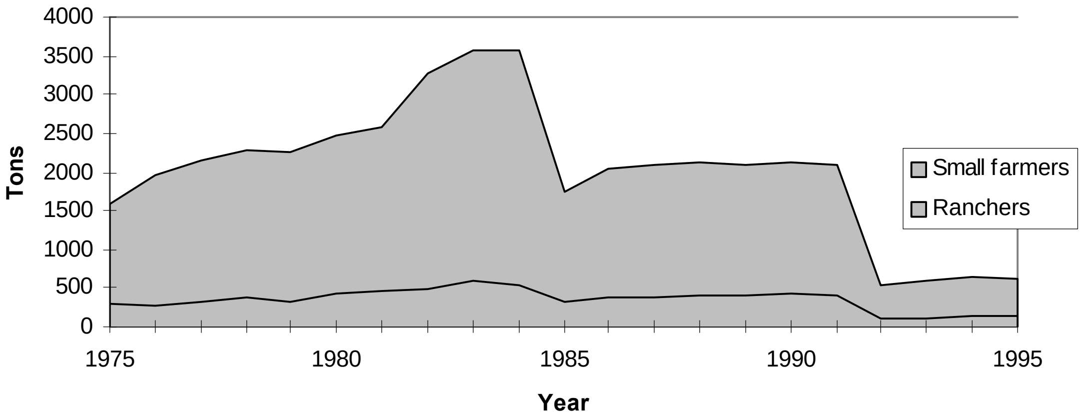


Figure 17: Simulated erosion aggregated by sector

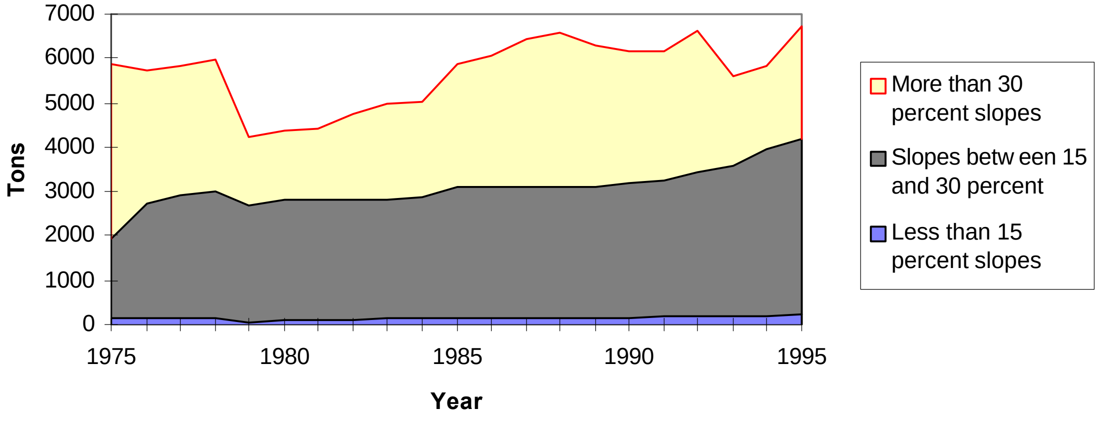


Figure 18: Simulated soil depth in three land units

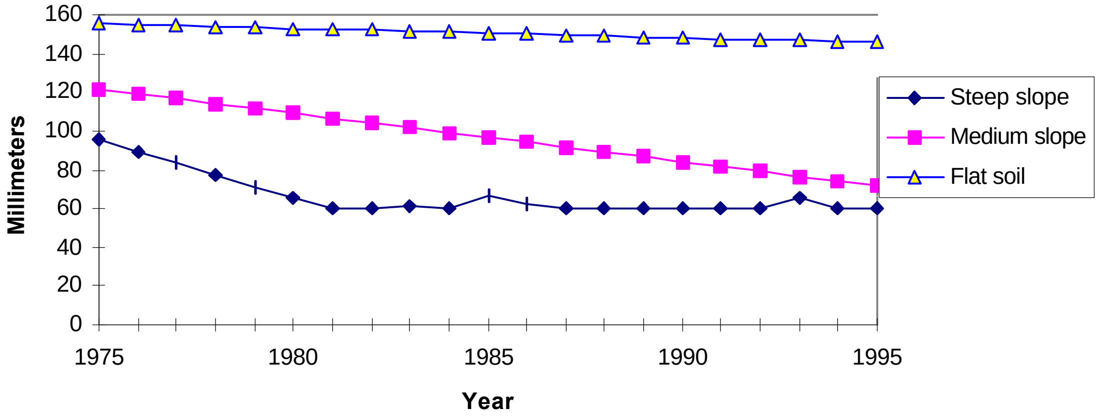


Figure 19: Simulated soil depth and soil conservation structure in one land unit

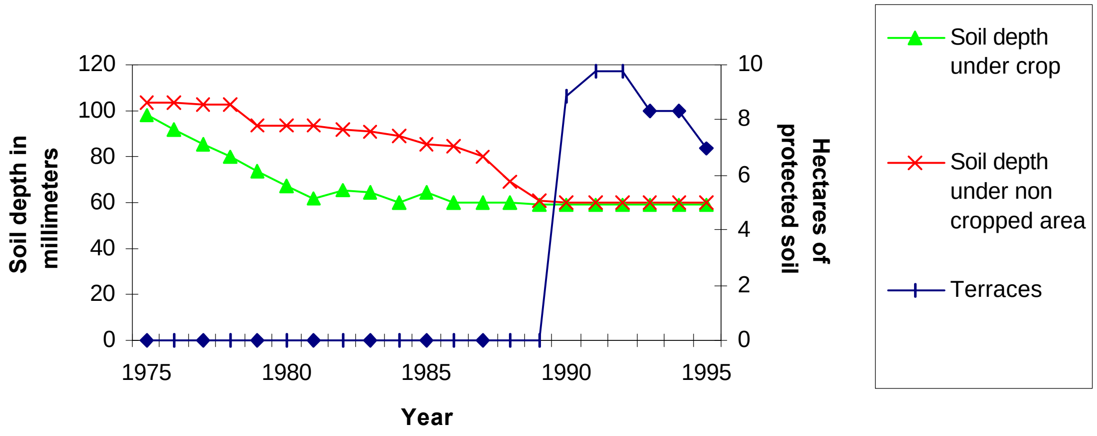


Figure 20: Simulated water volume in the outflow of the streams

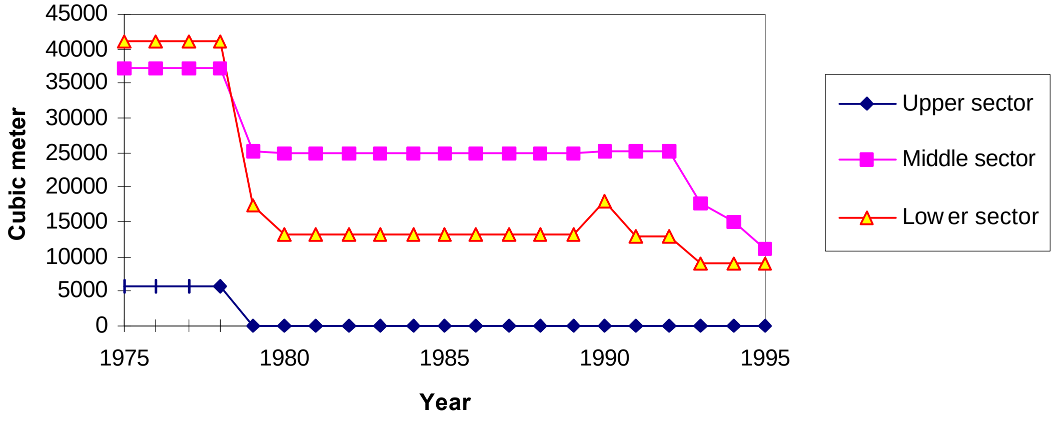


Figure 21: Shadow prices of land and labor

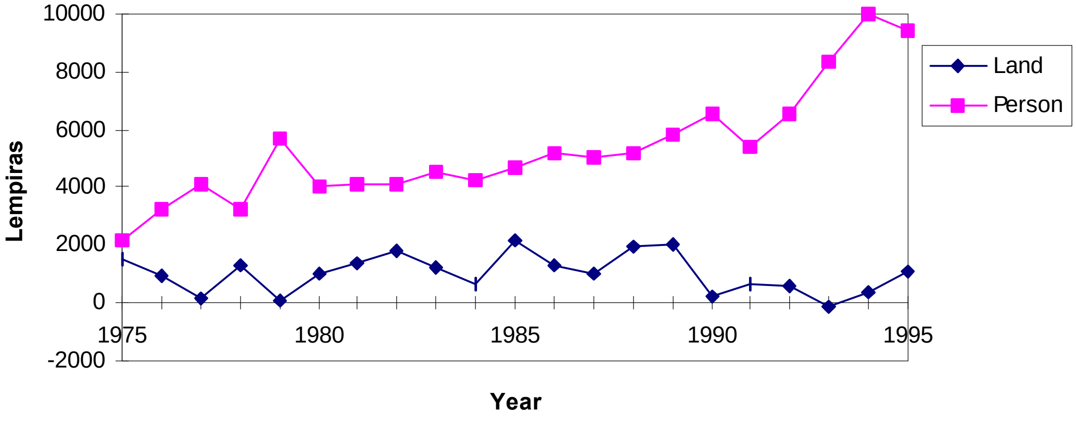


Figure 22: Simulated shadow prices of labor by season

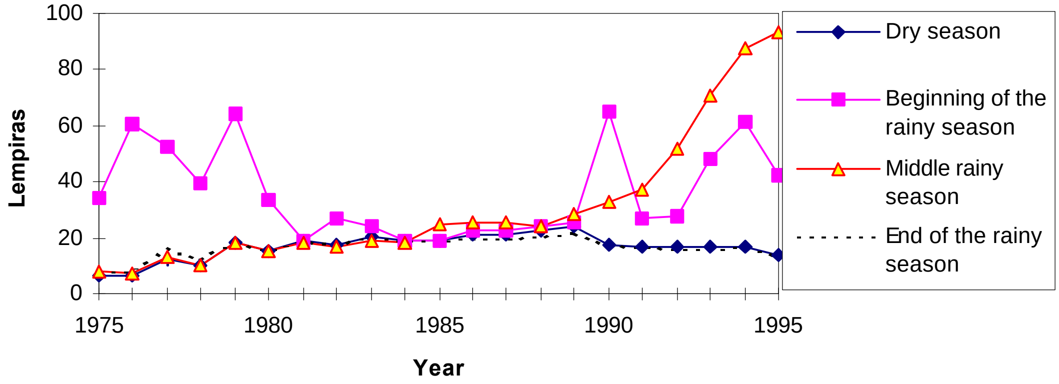


Figure 23: Shadow price of marketing constraint

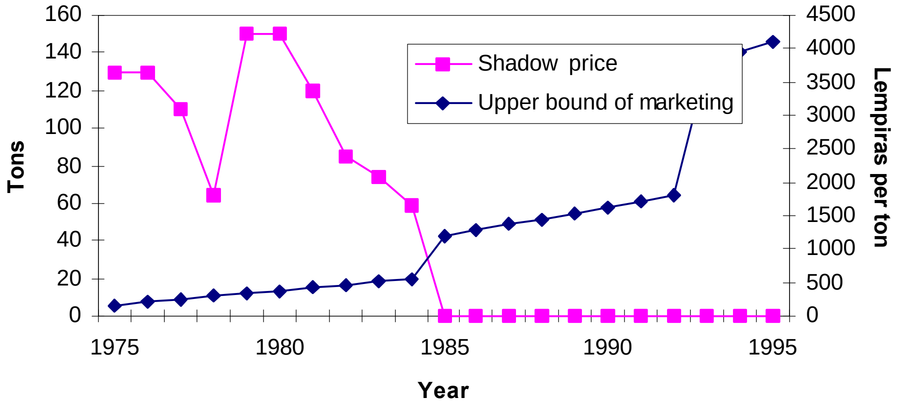


Figure 24: Shadow price of water by sector

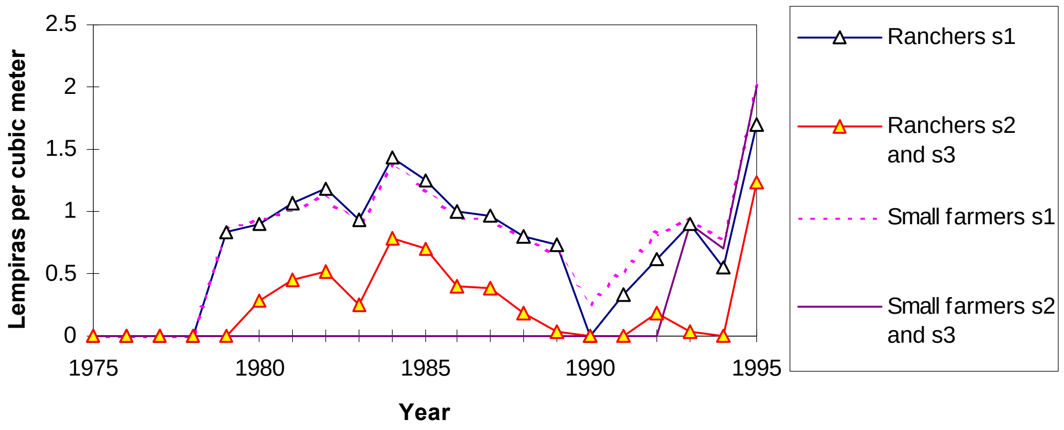


Figure 25: Per capita income
Alternative scenarios for population growth

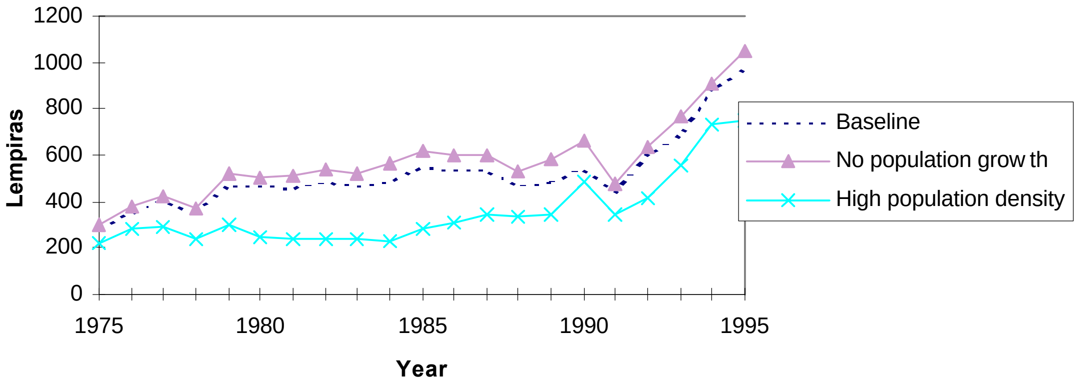


Figure 26: Simulated erosion
Alternative scenarios for population growth

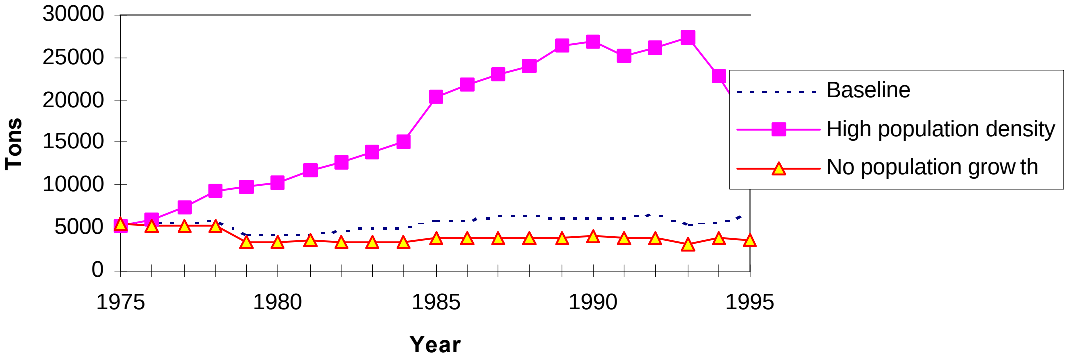
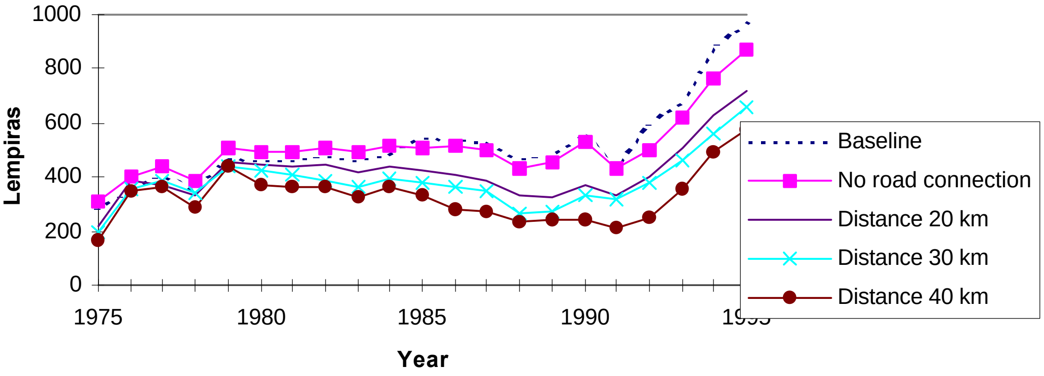


Figure 27: Per capita income
Alternative scenarios for access to market



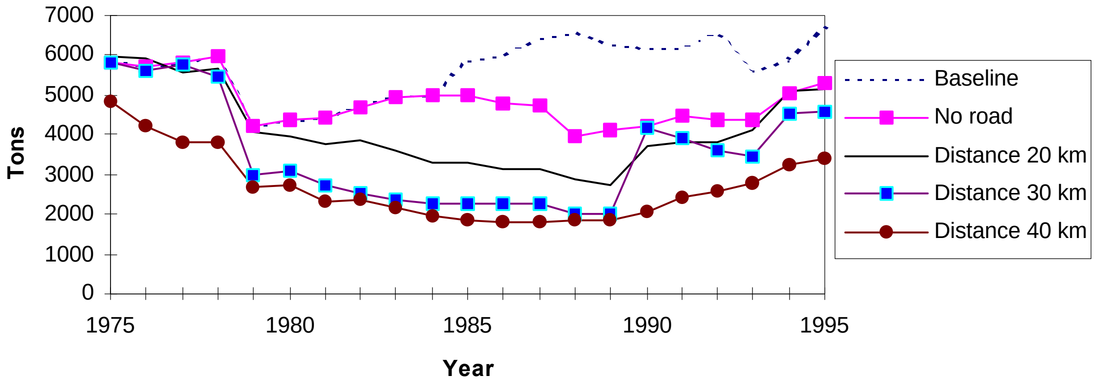


**Figure 28: Simulated erosion**
**Alternative scenarios for access to market**

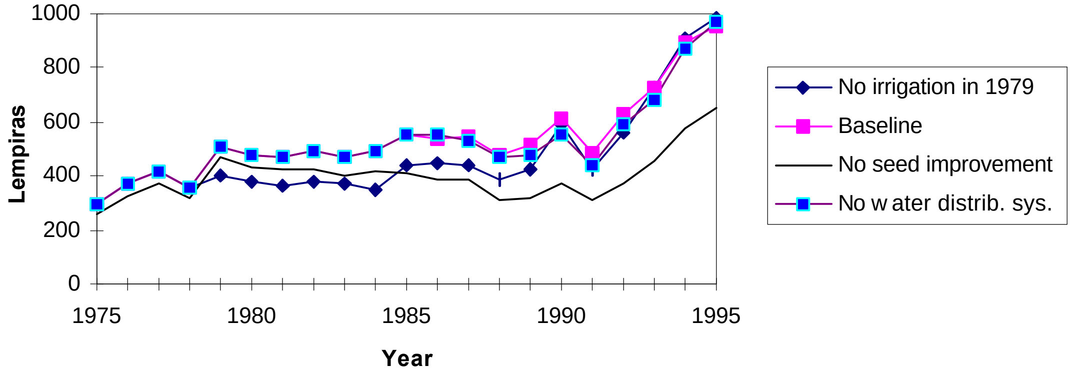


**Figure 29: Per capita income**
**Alternative scenarios for technologies**

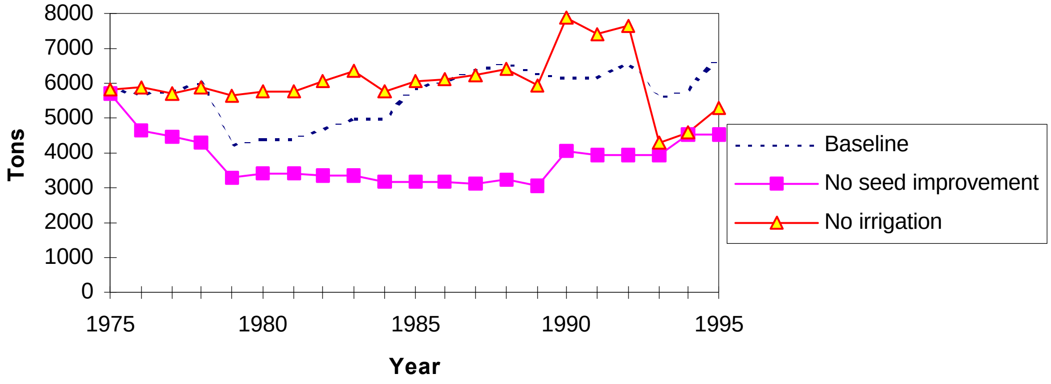


**Figure 30: Simulated erosion**
**Alternative scenarios for technologies**

**Figure 31: Per capita income**
**Alternative scenarios for natural resource constraints**

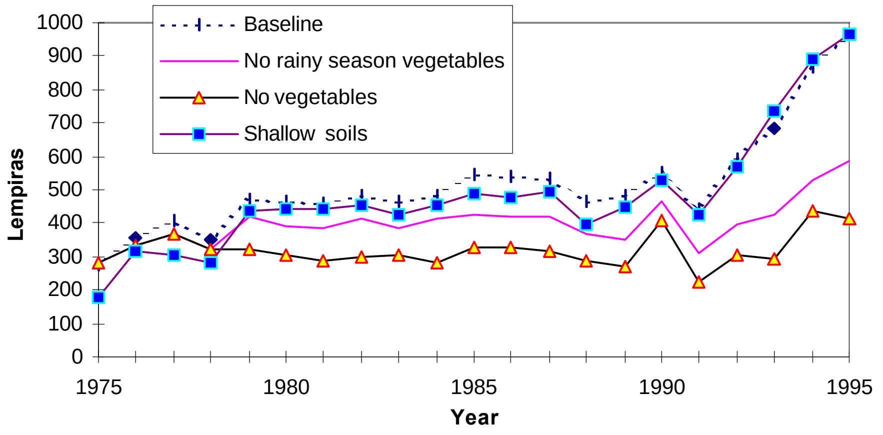


**Figure 32: Simulated erosion**
**Alternative scenarios for natural resource constraints**

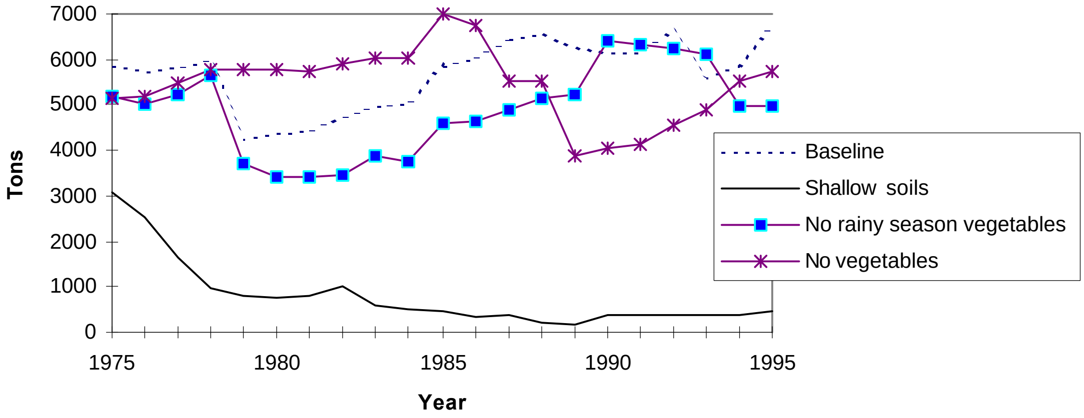


**Figure 33: Per capita income**
**Alternative scenario without market liberalization**

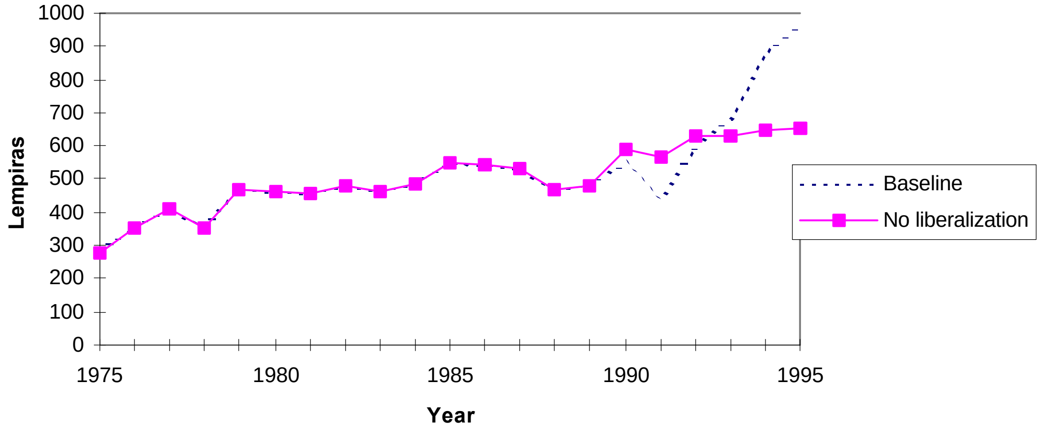


**Figure 34: Simulated erosion**
**Scenario without market liberalization**

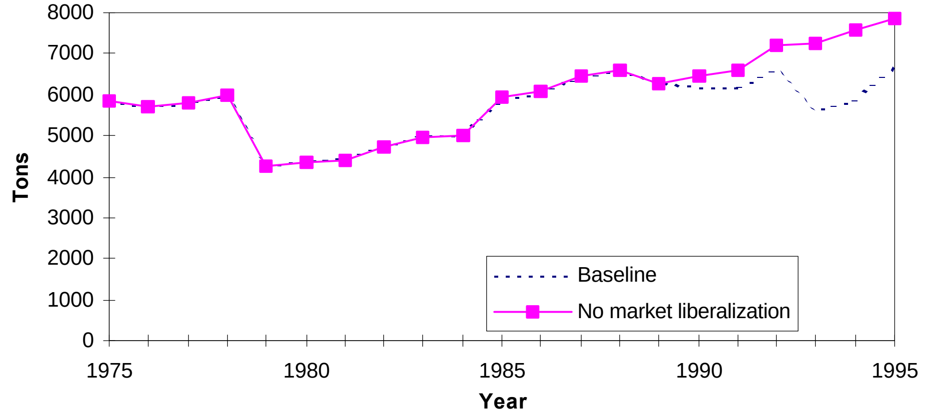


**Figure 35: Per capita income**
**Scenario without inorganic fertilizer**

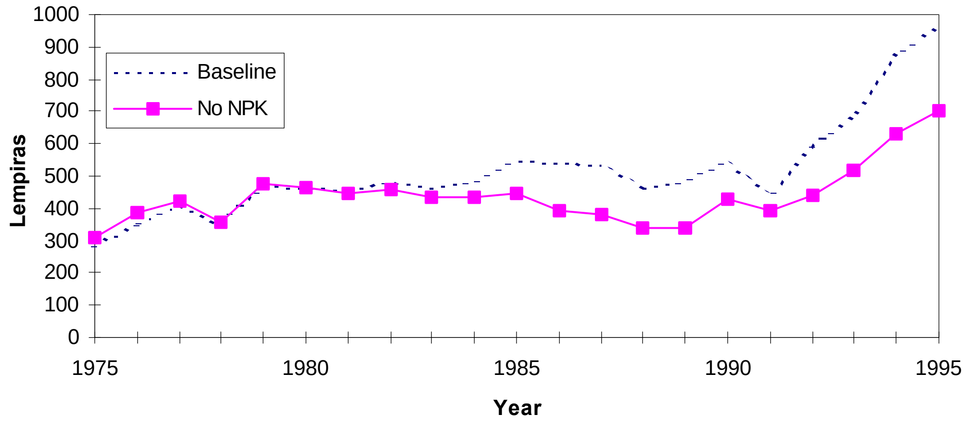
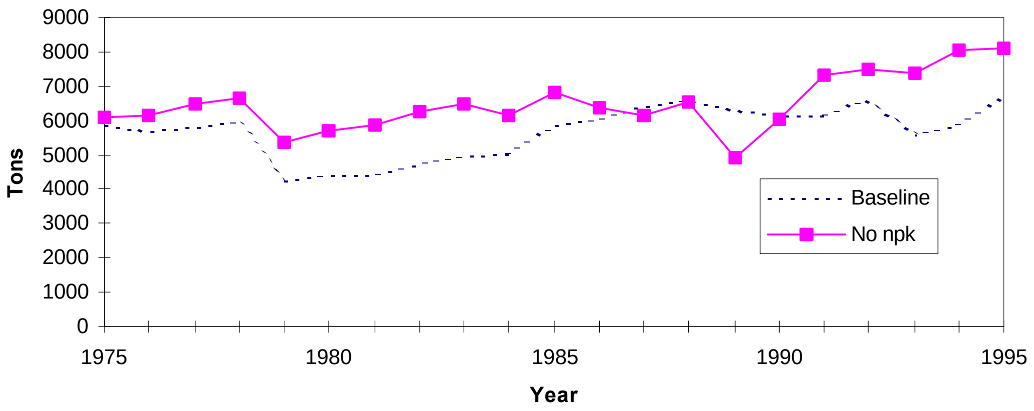


**Figure 36: Simulated erosion**
**Scenario without inorganic fertilizer**



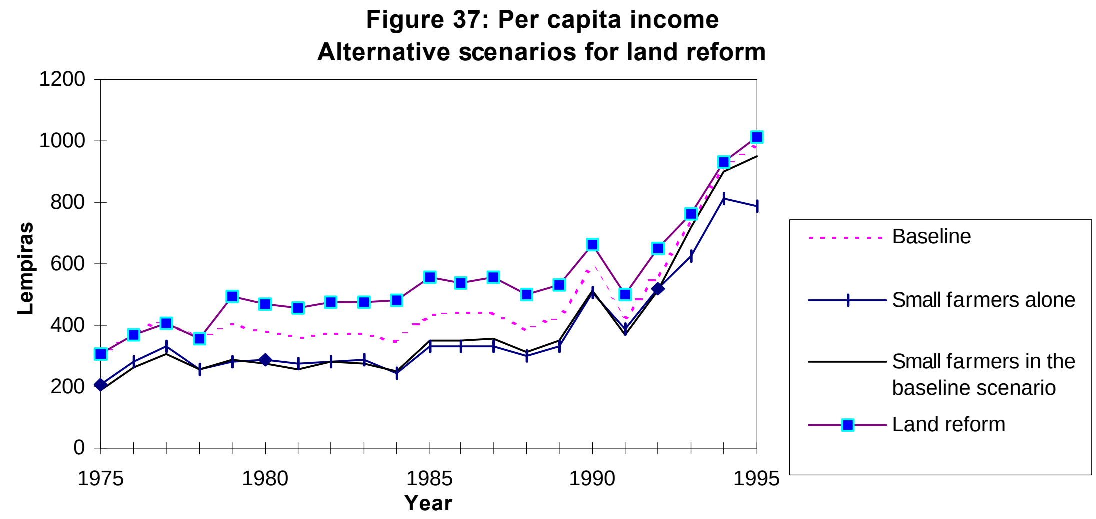


Figure 37: Per capita income
Alternative scenarios for land reform
Lempiras
1200
1000
800
600
400
200
0
1975
1980
1985
1990
1995
Year
Baseline
Small farmers alone
Small farmers in the baseline scenario
Land reform

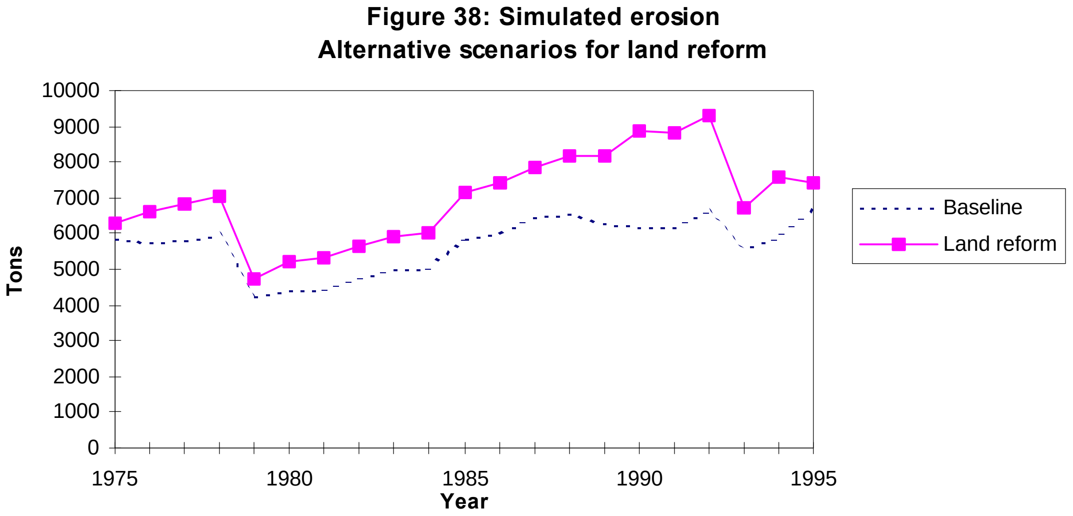


Figure 38: Simulated erosion
Alternative scenarios for land reform
Tons
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1975
1980
1985
1990
1995
Year
Baseline
Land reform

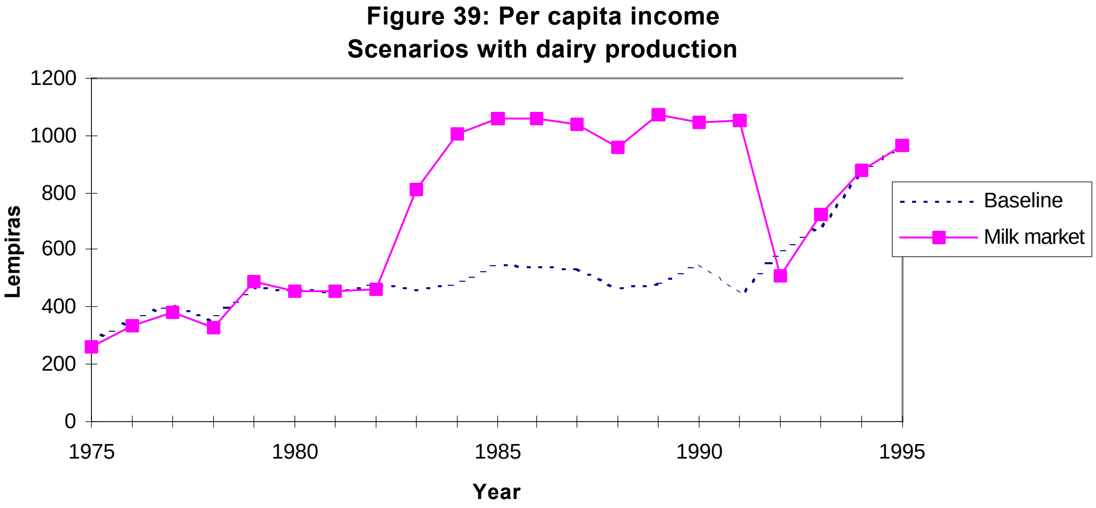


Figure 39: Per capita income
Scenarios with dairy production
Lempiras
1200
1000
800
600
400
200
0
1975
1980
1985
1990
1995
Year
Baseline
Milk market

**Figure 40: Simulated erosion**
**Scenarios with new markets**

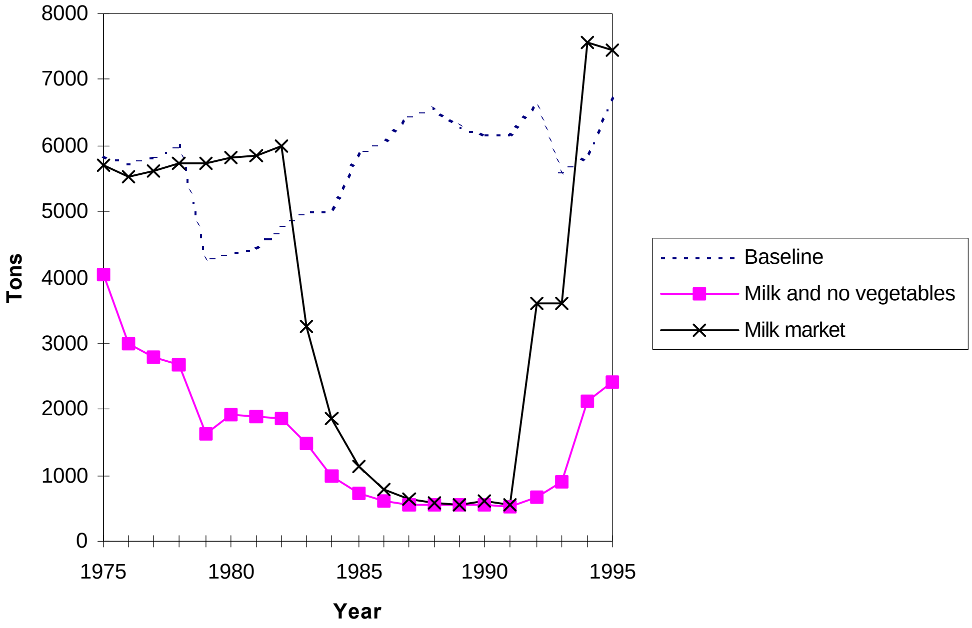


**Figure 41: Simulated land use**
**Long term baseline scenario**

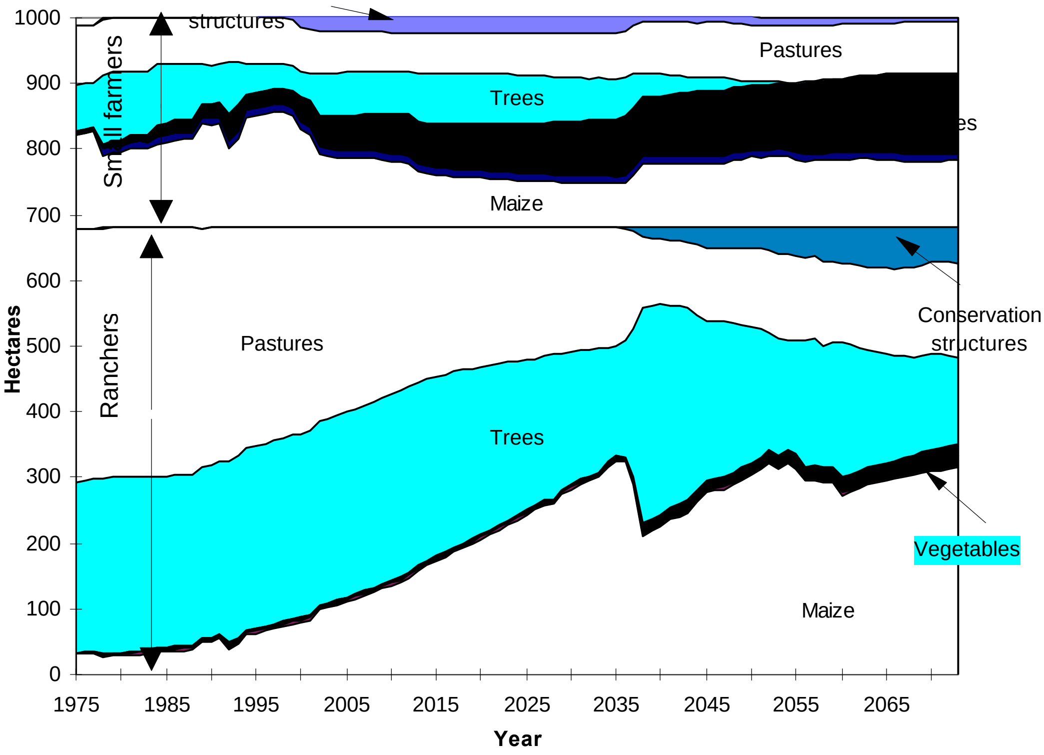


**Figure 42: Simulated erosion**
**Long term baseline scenario**

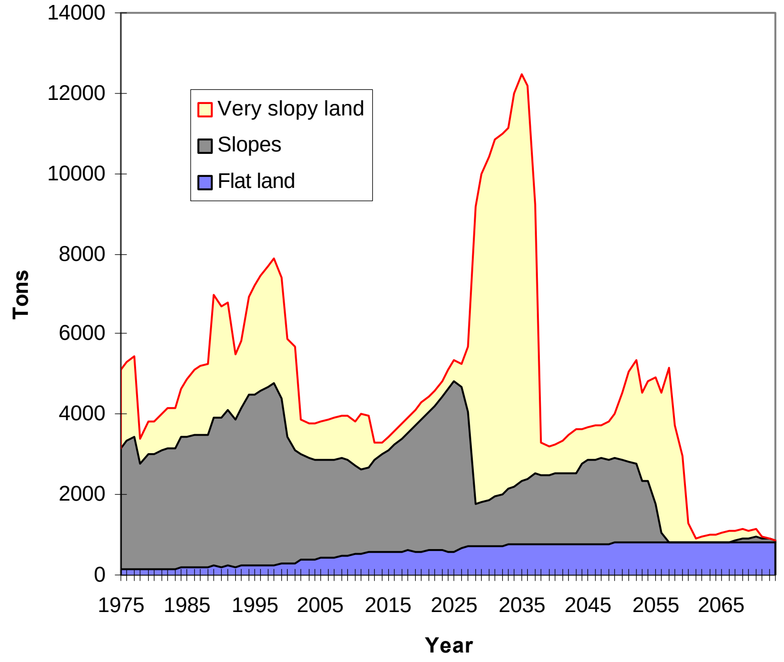


**Figure 43: Simulated conservation structures**
**Long term baseline scenario**

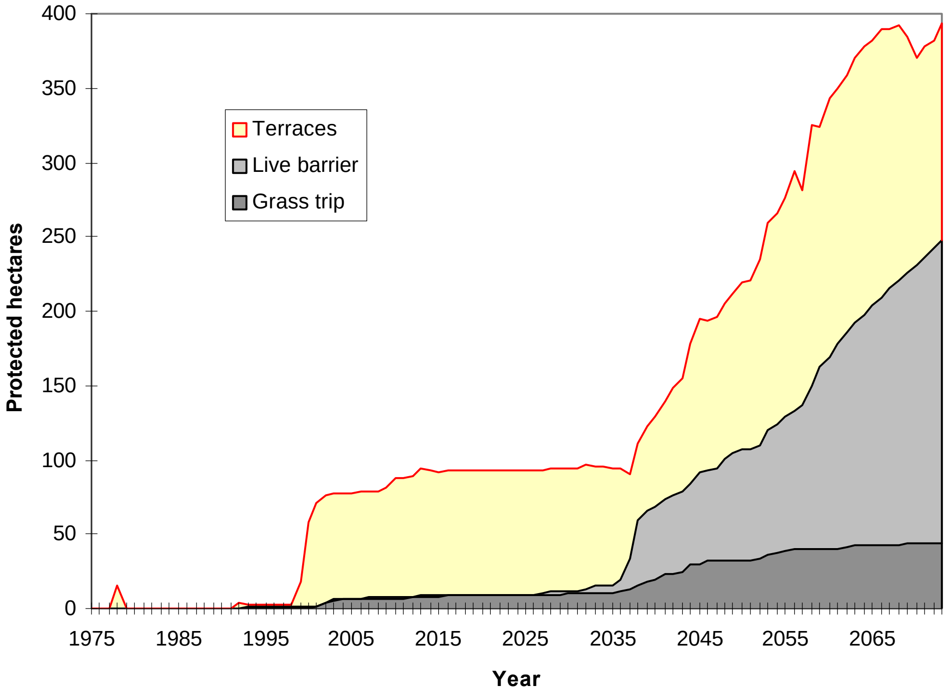


**Figure 44: Per capita income**
**Long term baseline scenario**

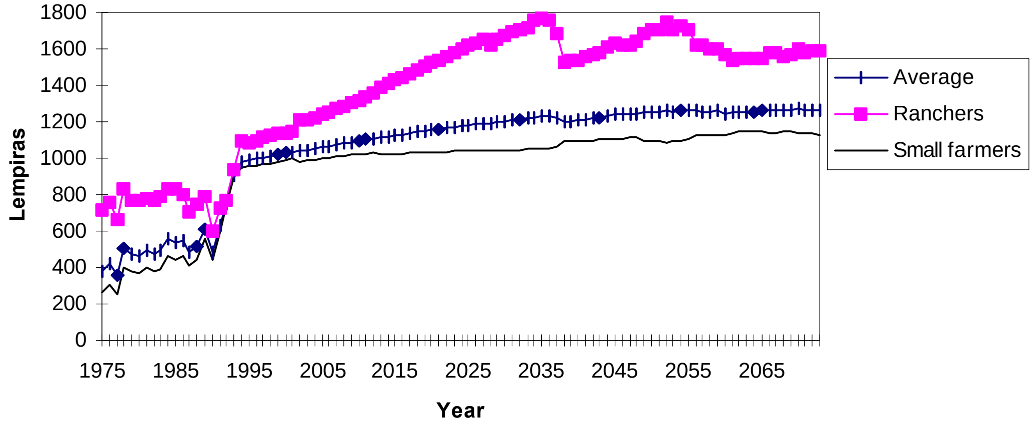


**Figure 45: Per capita income**
**Alternative scenarios for prices**

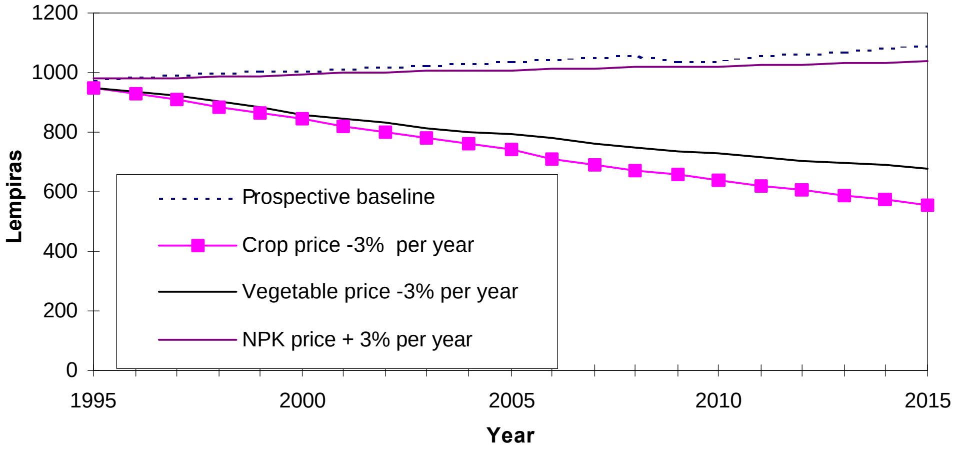
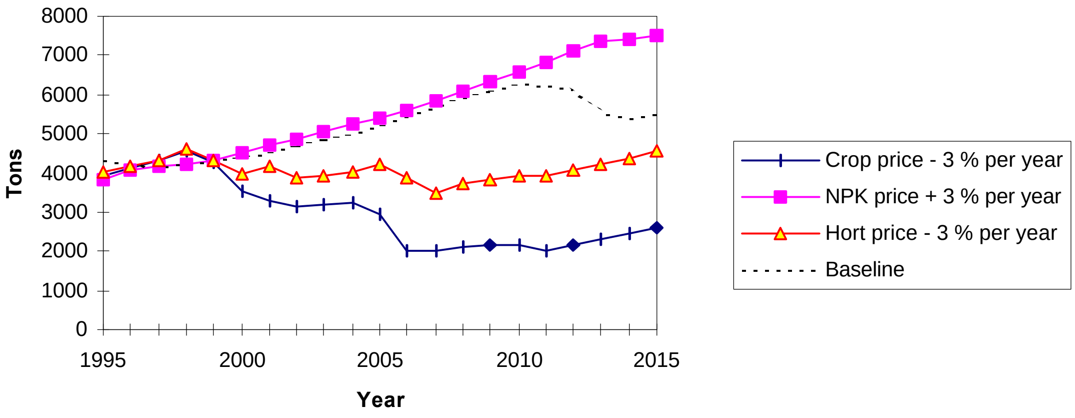


**Figure 46: Simulated erosion**
**Alternative scenarios for prices**



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# APPENDIX 1 : 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 sectors, and two types of households which leads to six groups of farmers. Each group has access to three types of soils varying by their slope. This leads to eighteen 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 and $a_3$ 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 trip), |
| *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 sectors 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 for various farm costs in local currency |
| CASHNPK | cash expenditure for conventional inputs in local currency |
| COMPOST | compost in tons |
| CONSER | conservation structures in hectares |
| CORRAL | manure produced by the corralling activity in tons |
| CROP | crop area in hectares |
| CUTCROP | abandoned crop area in hectares |
| CUTCONS | abandoned crop soil conservation structures |
| CUTGRAS | reduction of grass area in hectares |
| CUTIRRI | removal of the equipment of irrigation for one 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 |
| FAMLAB | family labor in days |
| EMIG | number of emigrants |
| EROSION | erosion volume in cubic meters |
| EROSIONG | erosion volume under forest and pasture in cubic meters |
| 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 sector |
| HELPINS | days of labor paid by one group to farmers from another group located in another sector |
| HELPOUT | days of labor sold by farmers to another group within the sector |
| HELPOUTS | days of labor sold by farmers to another group in another sector |
| HOEAREA | crop area that is cultivated by hand in hectares |
| IMMIG | number of immigrants |
| IRRI | irrigated area in hectares |
| KEROSEN | kerosene equivalent of one cubic meter of fuelwood |
| LABOR | total required labor 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 emigrants |
| MILK | total milk production in ton |
| NEWCROP | new cropped area in hectares |
| NEWIRRI | new irrigated area in hectares |
| NEWLIV | purchased livestock in standard tropical units |
| NEWCONS | new conservation structures in hectares |
| NEWGRAS | new pasture |
| 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 |
| RESIDU | crop residues used for compost and manure in tons |
| RESFEED | crop residues used as feed in tons |
| SAVING | savings in local currency |

| | |
|---|---|
| SEED | seeds coming from the last harvest in tons |
| SELCROP | crop sale in tons |
| SELLIV | livestock units sold |
| SELTREE | tree volume sold |
| SELMEC | mechanization units sold |
| SOILDEF | soil depth deficit in cubic meters |
| STOCK | grain stocks in tons |
| STRESS | plant water deficit in cubic meter |
| SURP | forage surplus in forage units |
| TREE | trees in cubic meters |
| TUTIL | total utility in local currency |
| TPROD | total crop production in tons |
| UTIL | annual utility in local currency |
| WATER | water used for irrigation |

**Coefficients**

| | |
|---|---|
| acth(p) | day of labor available per period |
| 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 ton 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 due to the use of hand tools instead of plow |
| deadwood(a) | volume of dead wood produced by one cubic meter of tree |
| demand(t) | exogenous demand for agricultural products |
| deprirr | annual rate of depreciation of irrigation devices |
| depmec | annual rate of depreciation of plow and weeder |
| depth(h,s,o) | agricultural soil volume in cropped area in cubic meter per hectare |
| depthg(h,s,o) | agricultural soil volume under pasture and forest in cubic meter per hectare |
| depmec | rate of depreciation of ploughs |
| dstfield(s) | average distance of field from the farm in kilometers |
| dstroad(s) | average distance of farm from the road in hectares |
| dpline | coefficient of depletion of land conservation structures in hectares |
| eros(o,c) | erosion in cubic meters per hectare |
| 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 |
| mule | weight potentially transported by a mule in tons per kilometer  per day |
| nitnman(p) | tons of organic nitrogen in one ton of manure |
| nitcom(p) | tons of organic nitrogen in one ton of compost |
| nitcor(p) | tons of organic nitrogen in one ton of corral product |
| nitnctr(p) | tons of organic nitrogen made available for crops where trees have been cut |
| nitnctg(p) | tons of organic nitrogen available for the next crop after the plowing of a pasture |
| nitcon | nitrogen, phosphorus or potassium content of NPK |
| niteffo(c,d) | additional production due to organic nitrogen use (tons/ton of nitrogen) |
| niteff(c,d) | additional production due to chemical fertilizers (tons/ton of nitrogen) |
| nitlim(c,d) | threshold of organic nitrogen effect on yield (tons/ton of nitrogen) |
| opport(p) | opportunity cost of leisure in local currency per day |
| per(p) | days of labor available per adult |
| popg | population growth rate |
| price(c,p) | crop prices per period in local currency per ton |
| price(l) | livestock prices per period in local currency per unit |
| pricecof | price of one ton of coffee in local currency |
| priceirr | prices of one irrigation system in local currency |
| priceker | price of kerosen  in local currency |
| pricemirr | yearly price for the maintenance of one irrigation system in local currency |
| pricemec | price of a plow in local currency |
| pricemilk | price of 1000 liters of milk in local currency |
| pricenpk | price per ton of chemical fertilizer |
| pricenc(a) | price per plant of coffee in local currency |
| pricenew | prices of young coffee trees |
| pricepur | price of purchased feed in local currency |
| pricebuy | price of purchased grain in local currency |
| price(a,y) | price of one cubic meter of fuelwood |
| 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 one ton of manure |
| seedn(c,p) | required quantity of seed in tons per hectare |
| soildp(d) | soil depth limit; bellow yields are affected |
| soiler(c,d) | soil erosion effect on yields |
| soilf(o) | erosion limitation by one hectare of forage crop |
| soilg(o) | erosion limitation by one hectare of grass |
| soilt(o) | erosion limitation by one cubic meter of trees |
| soilv(o) | threshold of  soil volume below which yields are affected in cubic meter |
| soill(o,k) | reduction in erosion by land conservation structures in cubic meters per hectare |
| soilp(c,d) | production loss due to soil loss in tons per ton of soil deficit |

| | |
|---|---|
| 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(p,c) | forage units provided by one ton of grain |
| ufsrp(p) | fraction of pasture grass or residue carried over into the next period |
| ufprc(p) | forage unit provided by one ton of purchased feed |
| uf(o,p) | forage units provided by one hectare of pastures on different type of soils |
| ufrs(p,c) | forage units provided by one ton of residues |
| wage(p) | wage of off-farm activities in local currency per period |
| watef(c,d) | effect of water deficit on yields in kilos per cubic meter |
| watp | water volume used by one person during the dry season in cubic meter |
| watn(c) | water volume required per hectare of crop during the dry season in cubic meter |
| wline(k) | weight of the stones necessary for one hectare of soil conservation structures |
| wirri | weight of irrigation devices in ton per hectare |
| woodn(p) | consumption of wood in cubic meters per person |
| wwood | weight of one cubic meter of wood |
| yldcof(a) | yield of coffee in ton per hectare |

### *Crop production*

There are two types of farms (h) per sector, three sectors (s) and three types of soils (o). In total it makes eighteen land units. Each land unit is covered by crops, trees, pastures and land conservation structures. c5 are crops cultivated during the rainy season. Crops from the dry season are constrained later by the irrigable area.

$$\sum_{c=1}^{C5} CROP_{h,s,o,c,t} + \sum_{a=1}^{A} \sum_{y=1}^{Y} TREE_{h,s,o,a,y,t} + GRASS_{h,s,o,t} + \sum_{k=1}^{K} areal_{k} \cdot CONSER_{h,s,o,k,t} = area_{h,s,o} \tag{1}$$

Land use change includes the expansion or the diminution of the cropped and the pasture areas. The same equation for trees and land conservation practices are written later.

$$CROP_{h,s,o,c,t-1} - CUTCROP_{h,s,o,c,t} + NEWCROP_{h,s,o,c,t} = CROP_{h,s,o,c,t} \tag{2}$$

Annual crop production is a function of yield (*avgy*) and area (*CROP*). There is a basic yield (avgy) which depends upon the type of soil (*o*) and the type of crop (*c*). This basic level of

$$GRAS_{h,s,o,t-1} - CUTGRAS_{h,s,o,t} + NEWGRAS_{h,s,o,t} = GRAS_{h,s,o,t} \tag{3}$$

production can be increased by applying chemical nitrogen *(nitcont· NPK*) or organic nitrogen (*NITORG*). Conversely, production would decrease with more superficial hand plowing (*HOE*), an insufficient soil depth (*SOILDEF*), erosion (*EROSION*), or a water deficit (*STRESS*).

$$\begin{aligned} TPROD_{h,s,o,c,t} &= avgy_{o,c} \cdot CROP_{h,s,o,c,t} \\ &- cr_c \cdot HOE_{h,s,o,c,t} \\ &+ \sum_{d=1}^{D} niteff_{c,d} \cdot nitcont_c \cdot NPK_{h,s,o,c,d,t} \\ &+ \sum_{d=1}^{D} niteff_{c,d} \cdot NITORG_{h,s,o,c,d,t} \\ &- \sum_{d=1}^{D} soilp_{c,d} \cdot SOILDEF_{h,s,o,c,d,t} \\ &- soiler_{c,o} \cdot EROSION_{h,s,o,c,t} \\ &- \sum_{d=1}^{D} watef_{c,d} \cdot STRESS_{h,s,o,c,d,t} \end{aligned} \tag{4}$$

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.

$$\begin{aligned} &spoil_{c,p} \cdot STOCK_{h,s,c,p-1,t} + harv_{c,p} \cdot TPROD_{h,s,o,c,t} - SELCROP_{h,s,c,p,t} \\ &- FOOD_{h,s,c,p,t} - FEED_{h,s,c,p,t} - SEED_{h,s,c,p,t} = STOCK_{h,s,c,p,t} \end{aligned} \tag{5}$$

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

$$\begin{aligned} & spoil_{c,p} \cdot STOCK_{h,s,c,plast,t-1} + harv_{c,p} \cdot \sum_{o=1}^{O} (TPROD_{h,s,c,t} - SEED_{h,s,o,c,t}) \\ & - SELCROP_{h,s,c,plast,t} - FOOD_{h,s,c,plast,t} \\ & - FEED_{h,s,c,plast,t} - SEED_{h,s,c,plast,t} = STOCK_{h,s,c,pl,t} \end{aligned} \tag{6}$$

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

$$seedn_{c,p} \cdot \sum_{o=1}^{O} CROP_{h,s,o,c,t} = \sum_{p=1}^{P} SEED_{h,s,c,p,t} \tag{7}$$

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

$$FOOD_{h,s,c_2,p,t} + BUY_{h,s,c_2,p,t} \geq cons_p \cdot POP_{h,s,t} - consd_p \cdot MIGRAT_{h,s,p,t} \tag{8}$$

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

$$\sum_{h=1}^{H} \sum_{s=1}^{S} \sum_{c=1}^{C} SELCROP_{h,s,c,p,t} \leq \sum_{c=1}^{C} demand_{c,p} \tag{9}$$

*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.

$$\begin{aligned} & (1 + form_{s,o}) \cdot GROUND_{h,s,o,t-1} - \sum_{c=1}^{C} (EROSION_{h,s,o,c,t} - depth_{s,o} \cdot CUTCROP_{h,s,o,c,t} \\ & + depthg_{s,o} \cdot NEWCROP_{h,s,o,c,t}) = GROUND_{h,s,o,t} \end{aligned} \tag{10}$$

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*).

$$(1 + form_{s,o}) \cdot GROUNDG_{h,s,o,t-1} - EROSIONG_{h,s,o,t} + depth_{s,o} \cdot \sum_{c=1}^{C} CUTCROP_{h,s,o,c,t} - depthg_{s,o} \cdot \sum_{c=1}^{C} NEWCROP_{h,s,o,c,t} = GROUNDG_{h,s,o,t} \tag{11}$$

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

$$\begin{aligned}\sum_{c=1}^{C} EROSION_{h,s,o,c,t} = & \sum_{c=1}^{C} (eros_{o,c} \cdot CROP_{h,s,o,c,t} \\ & - soiln_{o} \cdot \sum_{d=1}^{D} NPK_{h,s,o,c,d,t} \\ & - soilo_{o} \cdot \sum_{d=1}^{D} NITORG_{h,s,o,c,d,t}) \\ & - \sum_{k=1}^{K} soill_{o,k} \cdot CONSER_{h,s,o,k,t}\end{aligned} \tag{12}$$

Erosion in pasture and forest:

$$\begin{aligned}EROSIONG_{h,s,o,t} = & \, erosg_{o} \cdot GRASS_{h,s,o,t} \\ & + erosf_{o} \cdot agarea_{a,y} \cdot \sum_{a=1}^{A} \sum_{y=1}^{Y} TREE_{h,s,o,a,y,t}\end{aligned} \tag{13}$$

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

$$GROUND_{h,s,o,t} \geq soilv_{s,o} \cdot \sum_{c=1}^{C} CROP_{h,s,o,c,t} - \sum_{c=1}^{C} \sum_{d=1}^{D} SOILDEF_{h,s,o,c,d,t} \tag{14}$$

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

$$SOILDEF_{h,s,o,c,d,t} \leq soildp_{d} \cdot CROP_{h,s,o,c,t} \tag{15}$$

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

$$\begin{aligned}&(1 - dpline_{k}) \cdot CONSER_{h,s,o,k,t-1} + NEWCONS_{h,s,o,k,t}\\ &- CUTCONS_{h,s,o,k,t} = CONSER_{h,s,o,k,t}\end{aligned} \qquad \textbf{(16)}$$

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

$$CONSER_{h,s,o,k,t} \leq \sum_{c=1}^{C} CROP_{h,s,o,c,t} \qquad \textbf{(17)}$$

*Water modeling*

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

$$IRRI_{h,s,t} = IRRI_{h,s,t-1} + NEWIRRI_{h,s,t} - CUTIRRI_{h,s,t} \qquad \textbf{(18)}$$

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

$$WATER_{h,s,t} = watc \cdot IRRI_{h,s,t} \qquad \textbf{(19)}$$

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

$$IRRI_{h,s,t} \leq \sum_{o=1}^{O} suit_{h,s,o} \cdot area_{h,s,o} \qquad \textbf{(20)}$$

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

$$WATER_{h,s,t} \geq \sum_{o=1}^{O} \sum_{c=1}^{C} (watn_{c} \cdot CROP_{h,s,o,c,t} - \sum_{d=1}^{D} STRESS_{h,s,o,c,d,t}) \qquad \textbf{(21)}$$

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

$$springs_s + STREAM_{h,s-1,t} - WATER_{h,s,t} - watp \cdot POP_{h,s,t} = STREAM_{h,s,t} \qquad \textbf{(22)}$$

*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, or temporary migration, are limited to a fraction of the population.

$$(1 + popg) \cdot POP_{h,s,t-1} + IMMIG_{h,s,t} - EMIG_{h,s,t} = POP_{h,s,t} \qquad \textbf{(23)}$$

For the sake of simplicity we aggregate the labor time of the different farm activities in one variable (*LABOR*). Labor time (*LABOR*), migration (*per(p)* · *MIGRANT*) time and leisure time (*LEISURE*), labor time in other farms from the same sector (*HELPOUT*), plus labor in other farms from other sectors (*HELPOUTS*) and a coefficient representing the time to walk from one farm to the other within a sector (*distf*) and between two sectors (*distfs*) has to be equal to the family labor plus the labor from other farmers from the same sector (*HELPIN*) and from other sectors (*HELPINS*).

$$\begin{aligned} & LABOR_{h,s,p,t} + per_p \cdot MIGRANT_{h,s,p,t} \\ & + LEISURE_{h,s,p,t} + distf \cdot HELPOUT_{h,s,p,t} + distfs \cdot HELPOUTS_{h,s,p,t} \\ & = FAMLAB_{h,s,t} + HELPIN_{h,s,p,t} + HELPINS_{h,s,p,t} \end{aligned} \qquad \textbf{(24)}$$

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

$$\begin{aligned} & FAMLAB_{h,s,p,t} + HELPOUT_{h,s,p,t} + HELPOUTS_{h,s,p,t} \\ & + MIGRANT_{h,s,p,t} \text{ =L= } acth_p \cdot POP_{h,s,t} \end{aligned} \qquad \textbf{(25)}$$

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

$$\sum_{h=1}^{H}\sum_{s=1}^{S} HELPINS_{h,s,p,t} = distfs \cdot \sum_{h=1}^{H}\sum_{s=1}^{S} HELPOUTS_{h,s,p,t} \tag{26}$$

This equation ensure the equilibrium of supply and demand of wage labor within each sector.

$$\sum_{h=1}^{H} HELPIN_{h,s,p,t} = \sum_{h=1}^{H} distf \cdot HELPOUT_{h,s,p,t} \tag{27}$$

*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.

$$\begin{aligned}\sum_{c=1}^{C}\sum_{d=1}^{D} NITORG_{h,s,o,c,d,t} \leq \sum_{p=1}^{P} ( & nitnman_p \cdot MANURE_{h,s,o,p,t} + nitcor_p \cdot CORRAL_{h,s,o,p,} \\ & + nitcom_p \cdot COMPOST_{h,s,o,p,t} + nitnctr_p \cdot \sum_{a=1}^{A}\sum_{y=1}^{Y} CUTREE_{h,s,o,a,p,y,t} \\ & + nitnctg_p \cdot CUTGRAS_{h,s,o,p,t})\end{aligned} \tag{28}$$

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

$$NITORG_{h,s,o,c,d,t} + nitcon_c \cdot NPK_{h,s,o,c,d,t} \leq nitlim_{c,d} \cdot CROP_{h,s,o,c,t} \tag{29}$$

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

$$RESFEED_{h,s,o,c,t} + RESIDU_{h,s,o,c,t} \leq resid_c \cdot TPROD_{h,s,o,c,t} \qquad \textbf{(30)}$$

Manure *(MANURE)* and compost *(COMPOST)* production is limited by the amount of crop residue available ($rsd \cdot RESIDU$).

$$\sum_{o=1}^{O} \sum_{p=1}^{P} MANURE_{h,s,o,p,t} + \sum_{o=1}^{O} \sum_{p=1}^{P} COMPOST_{h,s,o,p,t} \leq rsd_c \cdot \sum_{o=1}^{O} \sum_{c=1}^{C} RESIDU_{h,s,o,c,t} \qquad \textbf{(31)}$$

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

$$\sum_{o=1}^{O} \sum_{p=1}^{P} MANURE_{h,s,o,p,t} + \sum_{o=1}^{O} \sum_{p=1}^{P} CORRAL_{h,s,o,p,t} \leq refus_p \cdot \sum_{l=1}^{L} ( LIV_{h,l,s,t} + \sum_{p=1}^{P} SELLIV_{h,l,s,p,t}) \qquad \textbf{(32)}$$

*Livestock modeling*

The energy requirements (*uf*) of the resident livestock (*LIV* and *SOLDLIV*) 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 has not been consumed during period *p-1* is carried over into period *p*.

$$\sum_{l=1}^{L} uf_{p,l} \cdot (LIV_{h,s,l,t} + SELLIV_{h,s,l,p,t}) + SURP_{h,s,p,t}$$
$$\leq \sum_{o=1}^{O} uf_{s,p} \cdot GRASS_{h,s,o,t} + \sum_{c=1}^{C} \sum_{o=1}^{O} uf_{c,p} \cdot FEED_{h,s,o,c,p,t}$$
$$+ \sum_{o=1}^{O} \sum_{c=1}^{C} ufrs_{o,c} \cdot RESFEED_{h,s,o,c,t} \qquad \textbf{(33)}$$
$$+ uf_{p,prc} \cdot PURC_{h,s,p,t} + uf_{p,srp} \cdot SURP_{h,s,p-1,t}$$

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

$$milkp \cdot pcow \cdot LIV_{h,s,l_1,t} = MILK_{h,s,t} \qquad \textbf{(34)}$$

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*).

$$\sum_{o=1}^{O} \sum_{c=1}^{C} MECAREA_{h,s,o,c,t} \leq lmec \cdot MEC_{h,s,t} \qquad \textbf{(35)}$$

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

$$MECAREA_{h,s,o,c,t} + HOEAREA_{h,s,o,c,t} = CROP_{h,s,o,c,t} \qquad \textbf{(36)}$$

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

$$tract \cdot MEC_{h,s,t} \leq LIV_{h,s,l_2,t} \qquad \textbf{(37)}$$

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 ($LIV_3$) requires the assistance of one person.

$$DMEC_{h,p,t} \leq acth_{p} \cdot LIV_{h,s,l3,t} \qquad \textbf{(38)}$$

Inputs, manure, wood and productions 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.

$$\begin{aligned}
& \sum_{o=1} dstfield_{s} \cdot (MANURE_{h,s,o,p,t} + dstfield_{s} \cdot COMPOST_{h,s,o,p,t}) \\
& + \sum_{c=1}^{C} dstroad_{s} \cdot SELCROP_{h,s,c,p,t} + dstroad_{s} \cdot PURC_{h,s,p,t} \\
& + \sum_{o=1}^{O} \sum_{a=1}^{A} dstroad_{s} \cdot wwood \cdot SELTREE_{h,s,o,a,p,t} \\
& + dstroad_{s} \cdot BUY_{h,s,p,t} \\
& + \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{d=1}^{D} (dstfield_{s} + dstroad_{s}) \cdot NPK_{h,s,o,c,d,t} \qquad \textbf{(39)} \\
& + dstfield_{s} \cdot harv_{p} \cdot \sum_{c=1}^{C} \sum_{o=1}^{O} TPROD_{h,s,o,c,t} \\
& + \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{k=1}^{K} dstfield_{s} \cdot wline_{k} \cdot NEWCONS_{h,s,o,c,k,p,t} \\
& + \sum_{s=1}^{S} \sum_{o=1}^{O} \sum_{c=1}^{C} dstfield_{s} \cdot RESIDU_{h,s,o,c,t} + dstfield_{s} \cdot woodn_{p} \cdot wwood \cdot POP_{h,s,t} \\
& \leq mule \cdot DMEC
\end{aligned}$$

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

$$\begin{aligned}
& (1 + depmec) \cdot MEC_{h,s,t-1} + \sum_{p=1}^{P} (NEWMEC_{h,s,p,t} \qquad \textbf{(40)} \\
& - SELMEC_{h,s,p,t}) = MEC_{h,s,t}
\end{aligned}$$

*Forest modeling*

Energy necessary for cooking comes from wood and from kerosene.

$$\sum_{p=1}^{P} woodn_{P} \cdot POP_{h,s,t} \leq KEROSEN_{h,s,t} + WOOD_{h,s,t}$$

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

$$\begin{aligned} \sum_{h=1}^{H}\sum_{s=1}^{S} WOOD_{h,s,t} \leq {} & \sum_{h=1}^{H}\sum_{s=1}^{S}\sum_{o=1}^{O}\sum_{a=1}^{A}\sum_{p=1}^{P} deadwood_{a} \cdot TREE_{h,s,o,a,y4,t} \\ & + \sum_{h=1}^{H}\sum_{s=1}^{S}\sum_{o=1}^{O}\sum_{a=1}^{A}\sum_{y=1}^{Y}\sum_{p=1}^{P} (CUTREE_{h,s,o,a,y,p,t} + CUTREEG_{h,s,o,a,y,p,t}) \end{aligned} \tag{42}$$

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 *CUTTREE*G is the wood volume cut from the trees located in the pasture.

$$\begin{aligned} & (1 + agrprt_{s,a}) \cdot TREE_{h,s,a,y-1,t-1} + \sum_{p=1}^{P} (NEWTREE_{h,s,a,p,y,t} \\ & - CUTREE_{h,s,a,p,y,t} - CUTREEG_{h,s,a,p,y,t} \\ & - SELTREE_{h,s,a,p,y,t}) = TREE_{h,s,a,y,t} \end{aligned} \tag{43}$$

*Utility function*

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

$$TUTIL = \sum_{h=1}^{H} \sum_{s=1}^{S} \sum_{=1}^{T} \left(\frac{1}{1+r}\right)^{t} \cdot UTIL_{h,s,t} \qquad \textbf{(44)}$$

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.

$$\begin{aligned}
UTIL_{h,s,t} = {} & \sum_{c=1}^{C} \sum_{p=1}^{P} price_{c,p} \cdot SELCROP_{h,s,c,p,t} \\
& + \sum_{l=1}^{L} \sum_{p=1}^{P} price_{l} \cdot (SELLIV_{h,s,l,p,t} - NEWLIV_{h,s,l,p,t}) \\
& + \sum_{l=1}^{L} price_{l} \cdot (LIV_{h,s,l,t} - LIV_{h,s,l,t-1}) + pricemilk \cdot MILK_{h,s,t} \\
& + \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{p=1}^{P} \sum_{y=1}^{Y} price_{a,y} \cdot SELTREE_{h,s,o,a,y,p,t} \\
& - \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{p=1}^{P} pricenc_{a} \cdot NEWTREE_{h,s,o,a,p,t}) \qquad \textbf{(45)} \\
& + \sum_{o=1}^{O} \sum_{a=1}^{A} \sum_{y=1}^{Y} price_{a,y} \cdot (TREE_{h,s,o,a,y,t} - TREE_{h,s,o,a,y,t-1}) \\
& + \sum_{o=1}^{O} pricecoffe \cdot yldcof_{a} \cdot TREE_{h,s,o,a_4,y_4,t} \\
& + \sum_{p=1}^{P} wage_{p} \cdot MIGRANT_{h,s,p,t} + \sum_{p=1}^{P} \\
& - \sum_{o=1}^{O} depirr \cdot IRRI_{h,s,o,t} - depmec \cdot MEC_{h,s,t} \\
& - CASH_{h,s,t} + \sum_{p=1}^{P} opport_{p} \cdot LEISURE_{h,s,p,t}
\end{aligned}$$

In the next equation the costs are aggregated.

$$\begin{aligned}
& pricemirr \cdot \sum_{o=1}^{O} IRRI_{h,s,o,t} + \sum_{o=1}^{O} \sum_{p=1}^{P} priceirr \cdot NEWIRRI_{h,s,o,p,t} \\
& + \sum_{p=1}^{P} pricepur \cdot PURC_{h,s,p,t} + \sum_{c=1}^{C} \sum_{p=1}^{P} pricebuy \cdot BUY_{h,s,c,p,t} \\
& + priceker \cdot KEROSEN_{h,s,t} + pricemec \cdot \sum_{p=1}^{P} NEWMEC_{h,s,p,t} \\
& \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{d=1}^{D} pricenpk \cdot NPK_{h,s,o,c,d,t} + \sum_{o=1}^{O} \sum_{c=1}^{C} cost_c \cdot CROP_{h,s,o,c,t} \\
& \leq CASH_{h,s,t}
\end{aligned} \qquad \textbf{(46)}$$