# Policy Analysis for Sustainable Land Management and Food Security in Ethiopia

*A Bioeconomic Model with Market Imperfections*

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# Foreword

Soil fertility and the lack of fertilizer use in Africa are frequently discussed topics. The problems of land degradation and low agricultural productivity, which result in food insecurity and poverty, are particularly severe in the rural highlands of Ethiopia. In many areas, a downward spiral of land degradation and poverty appears to be occurring. Finding solutions to these problems requires identifying effective entry points for farmers, governments, and civil society organizations, and understanding the potential impacts and tradeoffs that are likely to arise from alternative interventions. This report seeks to improve that understanding, using a bioeconomic model of land management and agricultural production developed for a community that is fairly typical of the situation in the Ethiopian highlands.

The report assesses the potential impacts of several policy options on small farmers' land management, productivity, food security, and poverty—including increased access to fertilizer credit, food-for-work programs, other off-farm employment opportunities, and promotion of tree planting on uncultivated land. The authors find that increased use of fertilizer credit could help to increase agricultural productivity, food security, and income, but could undermine farmers' incentives to invest in soil and water conservation, leading to greater land degradation. Increased employment opportunities through food-for-work or other measures can help to substantially increase household incomes, but would likely reduce food production and soil conservation, unless such measures are linked to conservation requirements. Promotion of tree planting on degraded land could increase incomes significantly without compromising food production or soil conservation, and, if combined with conservation incentives through food-for-work or other programs, could result in improved land management as well as increased incomes and food security.

These findings should be useful to policymakers and others seeking to improve land management and reduce poverty in Ethiopia and other countries where such problems are severe. Beyond this, the modeling approach developed by Stein Holden, Bekele Shiferaw, and John Pender can be usefully adapted and applied in many other African settings.

Joachim von Braun
Director General, IFPRI

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# Summary

Ethiopia is one of the poorest countries in the world. Most of its population of more than 65 million people lives in the highlands, where land degradation and droughts threaten their food security. Highland households in less-favored areas are increasingly dependent on better market access or external assistance in order to avoid starvation.

Soil erosion in Ethiopia averages nearly 10 times the rate of soil regeneration, and the country's estimated rate of soil nutrient depletion is among the highest in Sub-Saharan Africa. Such land degradation reduces average agricultural productivity. It also increases farmers' vulnerability to drought by reducing soil depth and moisture-holding capacity. The combined effects of low productivity and ecosystem degradation lock the poor in a vicious cycle of poverty and environmental degradation.

The risk of inadequate rainfall appears to have increased in recent years. Global climate changes may be responsible for the recent increased incidence of drought in areas not affected by earlier droughts. Wars and misdirected government policies have also contributed to a vicious spiral of poverty, land degradation, and food insecurity.

There is a strong need for peace, better governance, and improved development policies to help break Ethiopia's Malthusian course and put communities onto more sustainable development paths on which poverty is reduced and food security is improved. Especially urgent is the need for alternative development strategies that address land degradation and food insecurity in less-favored areas, where drought risk is high or market access is poor.

## The Study Area

In the Andit Tid watershed community in the eastern Amhara region of the Ethiopian highlands, both household welfare and land quality are deteriorating rapidly. Crop production is highly subsistence oriented, but the trend during the past 20 years has shifted from households as net sellers of food grains to net buyers. Recent droughts have even made the region dependent on food aid. Households lack off-farm income sources to protect their livelihoods against drought or other shocks. Significant interventions are urgently needed to diversify income opportunities and reverse the alarming agro-ecosystem degradation that threatens to destroy livelihoods.

*Policy Analysis for Sustainable Land Management and Food Security* presents a bioeconomic model of this less-favored area in the Ethiopian highlands. The main reason for selecting this case study area is the unique availability of both biophysical and socioeconomic data covering a period of 15–20 years. The data provide a valuable opportunity to analyze the relationships between population pressure, poverty, and land degradation, and to test policies for reducing vulnerability and improving sustainable management of the resource base.

## Analytical Framework

Bioeconomic models are useful tools in policy analysis because they can reflect the biophysical as well as the socioeconomic conditions essential for decisionmaking within a specific

"bioeconomy." They may be used to explore the linkages between the ecology and the economy and the dynamic effects of these linkages over time. They first capture the essential elements leading to a specific development path within a specific bioeconomy and then make it possible to see how stable this development path is, or how sensitive it is to changes in initial conditions. This baseline model may serve as a starting point for "policy experiments" to assess the likely impact of alternative policy interventions. Such models have become increasingly popular in recent years in addressing issues related to agricultural land use.

The bioeconomic model used in this study analyzes the combined effects of land degradation, population growth, market imperfections, and increased risk of drought on household production, welfare, and food security in Andit Tid. It is also used to assess the impact of increased access to credit for fertilizer, off-farm income, food-for-work (FFW) interventions, and planting of eucalyptus trees as alternative strategies for local development.

## Reducing Poverty and Land Degradation

The model predicts that provision and adoption of credit for fertilizer, although risky, would lead to increased grain production and improved household welfare and food security. However, provision of credit for fertilizer has a negative effect on incentives to conserve land, resulting in higher erosion rates when such unlinked credit is provided. Linking a conservation requirement to the provision of fertilizer credit can mitigate this negative outcome. Overall, however, even the combination of conservation structures and high levels of fertilizer use cannot sustain crop yields, because erosion cannot be eliminated fully and soils in the area are shallow.

Better access to off-farm income can improve household income and reduce vulnerability to drought. It may, however, also reduce incentives for food production and land conservation. The effects of FFW on food production and farmland conservation may vary depending on how and for what activities FFW is used, on the characteristics of the labor market, and on the impact of conservation technologies on short-term agricultural yields. FFW programs may undermine food production and incentives to conserve land unless FFW is linked to land conservation or better land management. The participation of local communities; knowledge of farming systems, resource distribution, local markets, and prices; and awareness of how different interventions affect production, conservation, and welfare are all needed to avoid program design failures. FFW may be used to enhance food security and land conservation, provided that programs are compatible with local priorities.

Planting trees, especially eucalyptus, on agriculturally marginal land may be a promising option for Ethiopian farm households. When other employment opportunities are limited, planting eucalyptus on land unsuitable for crop production may substantially increase household income if market outlets for trees can be identified. Our analysis suggests that tree planting on marginal lands will not have severe negative effects on food production or land conservation.

The combination of tree planting and FFW for conservation appears to produce superior outcomes. A policy combining promotion of tree planting and conservation of cropland may achieve win-win benefits in terms of increased household incomes as well as more sustainable land use. Careful program design and implementation would be required to maximize such benefits.

Finding solutions to the downward spiral of land degradation and poverty requires identifying effective entry points for farmers, governments, and civil society organizations, as well as understanding the potential impacts and tradeoffs likely to arise from alternative interventions.

Our analysis of the Andit Tid watershed community should be useful to policymakers and others seeking to reduce poverty and improve land management in Ethiopia and other countries where such problems are severe. Beyond this, the bioeconomic modeling approach used in this study can be usefully adapted and applied in many other settings.

CHAPTER 1

# Introduction

Ethiopia is one of the poorest countries in the world. Most of its population of more than 65 million people lives in the highlands, where land degradation and droughts cause declining and highly variable land productivity that threatens the food security of these people. Soil erosion has been estimated to average 42 tons per hectare per year on cultivated lands in the highlands, nearly 10 times the rate of soil formation (Hurni 1993), and Ethiopia has among the highest estimated rates of soil nutrient depletion in sub-Saharan Africa (Stoorvogel and Smaling 1990). Such land degradation not only reduces average productivity, but it also increases farmers' vulnerability to drought by reducing soil depth and soil moisture holding capacity.

Changes in the global climate may also have caused an increase in the incidence of drought that has occurred recently in areas that were not affected by earlier droughts. Wars and misplaced government policies have contributed to the vicious spiral of poverty, land degradation, and food insecurity. There is a strong need for peace and improved policies that can help to break the country's Malthusian course and put communities onto more sustainable development paths where poverty is reduced and food security improved. Especially urgent is a need for alternative development strategies that address land degradation and food insecurity in less-favored areas where drought risk is higher or market access is poorer (Pender et al. 2001).

Policy-makers and technology development institutions have long neglected less-favored areas. Recent research by the International Food Policy Research Institute (IFPRI) has challenged the conventional wisdom that public investments in developing countries should emphasize investment in favored areas (Fan and Hazell 2000; Pender and Hazell 2000; Hazell et al. 2002). On the basis of a comparative advantage argument, IFPRI maintains that certain types of agricultural and non-agricultural activities can give high returns and contribute significantly to poverty reduction (Pender, Place, and Ehui 1999). A precondition is sufficient investment in infrastructure and local institutional capacity. More research is, however, necessary to investigate how large this potential is.

The behavioral and material determinants of production relationships lead to low investment levels and severe market imperfections (Binswanger and Rosenzweig 1986; Binswanger, McIntire, and Udry 1989), and these imperfections contribute to the problems of poverty and food insecurity. Improving markets may therefore be one important element in a new policy for sustainable development. There is nonetheless no guarantee that piecemeal improvements of some markets will lead to economic growth and more sustainable land use. It is even possible that improved access to some markets can lead to more land degradation. This is also consistent with the theory of second best (Lipsey and Lancaster 1956). Both the mixture and the sequencing of policies may matter for the outcomes.

Bioeconomic models may be useful tools in policy analysis because they can reflect the biophysical as well as socioeconomic conditions essential for decision-making in a specific "bioeconomy." They may be used to explore the linkages between the ecology and the economy and the dynamic effects of these linkages over time. They may thus be used first to capture the essential elements leading to a specific development path in a specific bioeconomy and to make it possible to see how stable or sensitive this development path is to changes in some of the initial conditions. Second, this baseline model may serve as a starting point for "policy experiments" to assess the impact of alternative policy interventions. Such models have become increasingly popular in recent years in addressing issues related to agricultural land use and intensification (e.g., Barbier and Bergeron 2001; Ruben, Kuyvenhoven, and Kruseman 2001; Shiferaw, Holden, and Aune 2001; Okumu et al. 2002; Vosti, Witcover, and Carpentier 2002; Holden 2004).

We have in this report developed a bioeconomic model for a "less favored," severely degraded, densely populated area with fairly good market access in the Ethiopian highlands. Even though the area is favorably located near the main road between Tigray and Addis Ababa, there are significant market imperfections[1] that affect land productivity in the area (Holden et al. 2001). We have very good biophysical as well as socioeconomic data from this area and can therefore rely less on theoretical assumptions and more on empirical reality when constructing the model.[2]

Our objective is to analyze the determinants of the development path in the study area, including land degradation, population growth, market characteristics, choice of technology, and the implications of increased production risk, using a dynamic bioeconomic model. Furthermore, we want to assess the impacts of alternative policies on poverty reduction, increased food security, and promotion of more sustainable land use in the study area. Specifically, we assess the impacts on land management, land degradation, household production, income, and food security of

1. Drought risk in combination with land degradation and population growth
2. Fertilizer credit
3. Improved access to off-farm income
4. Access to food-for-work (FFW) programs
5. Promotion of planting of eucalyptus on land unsuitable for crop production

In Chapter 2 we briefly describe the case study area. Some relevant issues in bioeconomic modeling are discussed and the basic structure of the bioeconomic model is outlined in Chapter 3, followed by a discussion of the methodology of bioeconomic modeling in Chapter 4. The results and discussion are presented in Chapter 5, followed by the conclusions. A detailed description of the model in GAMS programming language is provided in Appendix A.

[1]These market imperfections include imperfections in factor markets (land, labor, traction power), output markets, and intertemporal markets (credit, insurance).

[2]The data availability allowed us to apply flexible functional forms when estimating many relationships instead of relying on, for example, Cobb–Douglas production functions, or instead of assuming perfect markets or completely missing markets we specify more typical "in-between" situations with imperfectly functioning markets.

## CHAPTER 2

# Description of the Case Study Area and Data

Andit Tid was selected by the Soil Conservation Research Programme (SCRP) in collaboration with the Ethiopian Ministry of Agriculture as one of seven research stations in order to study as many different agro-climatic zones and land-use systems as possible in the Ethiopian highlands (Ludi 1997). Andit Tid is located approximately 60 kilometers east of Debre Berhan, along the main road between Addis Ababa and the Tigray Region, in East Shewa in the central Ethiopian highlands. This implies that the market access is fairly good. The area is classified as belonging to the low-potential cereal–livestock zone and is severely degraded. It is a high-altitude area (>3,000 meters above sea level [m.a.s.l.]). The land is located in two altitude zones: *dega* zone (<3,200 m.a.s.l.) and *wurch* zone (>3,200 m.a.s.l.). The average rainfall is 1,336 mm per year, distributed over two growing seasons, the *meher* season from June to November and the *belg* season from January to May. Droughts were not common in the area until very recently, when the *belg* rains failed in two consecutive years (1999 and 2000). Hailstorms and frost, however, have often damaged crops.

The two dominant soil types are *andosols* and *regosols.* Andosols dominate in the *wurch* zone while regosols dominate in the *dega* zone. Andosols are rich in organic matter. The grass turf is collected in heaps and burnt[3] before barley is planted. This releases nutrients for the crop but also causes considerable losses of organic matter and soil nitrogen. Yohannes (1989) estimated 75 percent of the land to be on steep slopes (>25 percent slope). Soil erosion rates in the area are very high, and a large share of the land has shallow soils, causing reduction of soil depth, which affects crop rooting depth and thus yields (Shiferaw and Holden 2001). Holden and Shiferaw (2000) estimated 21 percent of the land to have shallow soils (<30 centimeters soil depth) and 48 percent to be of medium depth (30–60 centimeters).

Various forms of conservation technologies are common in the area. They have been partly introduced through external food-for-work (FFW) programs. The farmers later removed more than 50 percent of the externally introduced conservation structures. Shiferaw and Holden (1998) found that human population pressure (land scarcity) increased the probability that conservation structures were partly or fully removed. The reasons for this were thought to be that the conservation structures did not contribute to increased yields in the short run, the structures occupied some land and therefore reduced the effective planting area, and the structures collected fertile soils that could be used to increase short-run production by dismantling the structures and spreading out the soil collected there. The structures could also harbor rats that may damage the crops.

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[3]Locally called *gaay.*

The main crop in the area is barley, followed by wheat, horse beans, and field peas. Lentils and linseeds are also commonly grown. Most of the crop production takes place in the *dega* zone, but barley is also grown in the *wurch* zone in the *belg* season.

Cattle and sheep are the dominant types of livestock, but goats, equines, and chickens are also common. The animal population density is very high in the area; Yohannes (1989) estimated it to be 1.48 tropical livestock units (TLU)[4] per hectare, compared to 0.36 as the average for the Ethiopian highlands. We found this density to have increased to 2.03 TLU per hectare in 1998 but it declined to 1.71 by the end of 1999 because of the drought (Holden and Shiferaw 2000). Fifty-three percent of the sampled households surveyed in 2000 had two or more oxen, 25 percent had one ox, and 22 percent had no oxen. The two-or-more-oxen household group farmed close to 70 percent of the land area and the no-oxen group close to 10 percent of the area.

The population density of the study area was estimated to be 230 persons per square kilometer of cultivable land in 1999 and was estimated to be 145.5 persons per square kilometer in 1986 (Yohannes 1989). The average population density was 61 persons per square kilometer for the Ethiopian highlands (Yohannes 1989). The population growth rate was estimated to be 3.0 percent per year, indicating a rapidly increasing population pressure.

Production of crops is well integrated with production of livestock in the area. Oxen are the dominant source of traction power. Hand cultivation is used only on very steep slopes inaccessible by oxen. Animal manure is used for fuel or as fertilizer on crops. Sale of animals is an important source of cash income. Crop residues are used as animal fodder. Fodder is otherwise obtained from fallow land and grazing land, but only a small share of this (5 percent) is from communal land. Fodder shortage is an important constraint, and purchase of fodder and use of cut-and-carry systems are the main strategies to overcome this problem, besides limiting the number of animals kept (Holden and Shiferaw 2000).

The land resources (land of different quality) are fairly evenly distributed in the area owing to frequent land redistributions in Ethiopia since the 1970s in which land was allocated based on household size. Livestock possession is therefore a better indicator of household wealth and wealth differentiation. Oxen ownership in particular signifies the farming capacity of households, as the rental market for oxen for plowing is highly imperfect (Holden and Shiferaw 2000; Holden, Shiferaw, and Pender 2001). It also leads to the typical pattern in which households without oxen rent out land to households with two oxen or more, while households with one ox exchange oxen among themselves. Land renting typically takes place in the form of share tenancy, in which the share to the owner varies between 0.5 and 0.25 depending on land quality. Households may have access to credit in kind for purchase of fertilizers but are reluctant to take this kind of credit even though it appears profitable to do so (based on data obtained from the extension agent in the area, we found barley responded well to fertilizer but wheat did not because of the high risk of frost damage).[5] Risk and high aversion to this type of risk cause households to be reluctant to buy fertilizer on credit.

Households have limited access to off-farm income sources. Crop production is highly subsistence oriented, but the trend during the last 20 years has shifted from

[4]One TLU is equivalent to one 250-kilogram animal.

[5]Credit utilization was found to be significantly positively correlated with number of educated males in the household, household size, land loss in recent land redistribution, and male sex of household head, and negatively correlated with livestock ownership and size of male labor force.

households being net sellers of food grains to being net buyers. The recent droughts have even made the area dependent on food aid (Holden and Shiferaw 2000).

The main reasons for selecting this case study area for bioeconomic modeling was the unique availability of both biophysical and socioeconomic data covering a greater than 15-year period. The SCRP started collection of biophysical data when a field station was established in 1982. These data included soil erosion data at plot and watershed levels, yield measurements, conservation technology experiments, soil chemical and physical analyses, and meteorological data. Household survey data were collected in 1986, 1993/94, 1997/98, and 1999/2000. These surveys also included detailed data collection at the farm plot level. The data provided a unique opportunity to analyze carefully the relationships between population pressure, poverty, land degradation, conservation, household production, and welfare, including food security.

# CHAPTER 3

# The Bioeconomic Model

## General Issues

There is a growing interest in using bioeconomic models as a tool for policy analysis to better understand pathways of development and to assess the impact of alternative policies on the natural resource base and human welfare (Barbier and Bergeron 2001; Ruben, Kuyvenhoven, and Kruseman 2001; Shiferaw, Holden, and Aune 2001; Okumu et al. 2002; Holden et al. 2003; Holden, Shiferaw, and Pender 2004). One of the potential benefits of these models is that one can get a better and more comprehensive indication of the feedback effects between human activity and natural resources. Modern computer power permits development of complex models far beyond what was possible only a few years ago. It has therefore become possible to make models that are theoretically more consistent and empirically more accurate.

The novelty of the model presented here is that it is a dynamic non-separable household model that simultaneously integrates economic optimization in production and consumption with intertemporal environmental feedbacks, allowing for nonlinearities in constraints as well as the objective function. Some other bioeconomic models have not been truly dynamic, as they have incorporated future impacts through sustainability constraints or user costs only (Holden 1993a,b; Shiferaw and Holden 1999, 2000; Kruseman 2000). This model is dynamic, that is, the households maximize discounted utility over a limited time horizon.

Earlier bioeconomic models have either been biological process models that do not incorporate human behavior in a comprehensive way through optimization; economic optimization models linked, although not simultaneously, to a biological simulation component; or models that resort to perfect market assumptions allowing a single decision maker to represent a large number of heterogeneous households (e.g., Okumu et al. 2002). While the latter may be a good simplification in bioeconomies in which markets function reasonably well, such models may not be a good representation of low-resource bioeconomies, as in the northern Ethiopian highlands, where markets typically are highly imperfect. The assumption of perfect markets results in separability of production behavior from consumption behavior (Singh, Squire, and Strauss 1986) and was therefore convenient and computationally necessary until recently. Theoretical and empirical research has shown that market imperfections have significant impacts on production decisions in low-resource agriculture, and this gives reason to question work based on perfect market assumptions. Rather, one should carefully examine the market characteristics, as they can alter not only the size but also the direction of responses of key outcome variables (de Janvry, Fafchamps, and Sadoulet 1991; Sadoulet and de Janvry 1995; Holden and Binswanger 1998).

Market imperfections and heterogeneity of resources across households cause land use at plot level to depend on household resources in the study area (Holden, Shiferaw, and Pender

2001). Models are therefore developed for different more homogeneous household categories.[6] The household data are carefully aggregated and checked for consistency across groups to resemble the actual pattern of household interactions through their participation in imperfect factor and output markets. These market imperfections include limited access to off-farm employment, price bands for outputs and labor, a constrained rental market for land through share tenancy, oxen rental through exchange with labor only, and constrained access to formal credit in kind (for fertilizer) or to informal credit at a high interest rate.

The model also incorporates risk-averse behavior through a constant partial relative risk aversion utility function, production risk due to drought, and downside risk aversion to taking credit for fertilizer. Drought also affects prices for crops and livestock and price expectations (covariate risk), and these have additional effects on household production and welfare.

Earlier optimization models were criticized for being linear while the reality they were supposed to represent was highly nonlinear. While piecewise linear representations of nonlinear relationships may serve as good and efficient approximations, the recent advances allowing for large nonlinear optimization models make optimization models more credible.

The model endogenizes the effects of land degradation in the form of soil erosion and nutrient depletion on household decisions; that is, the effects of land degradation on expected future productivity are taken into account in farmers' current decisions. The availability of biophysical data from conservation experiments in the study area allows us to estimate erosion rates as well as crop productivity responses on different soils in the study area. The model furthermore integrates crop and livestock interactions. Crop choice, building or removal of conservation structures on different types of land, fertilizer use, and manure use are endogenous decisions that affect the rate of land degradation. These decisions affect erosion and nutrient depletion rates that again determine crop productivity in later years.[7]

Agricultural production takes place in two cropping seasons per year, the *meher* and *belg* seasons. Recently, the *belg* season rains have failed in several consecutive years, although this was rare in the past. We attempt to model the effects of this new type of risk. The covariate drought risk also has consequences for market prices of agricultural commodities. Farm households face high cereal prices in drought years when they are likely to be net buyers of cereals. At the same time, livestock prices are depressed because many have to sell their animals to buy cereals or because of their inability to feed their animals. Expected incomes in normal years and drought years are therefore based on the expected outputs and expected prices in these two states of nature.

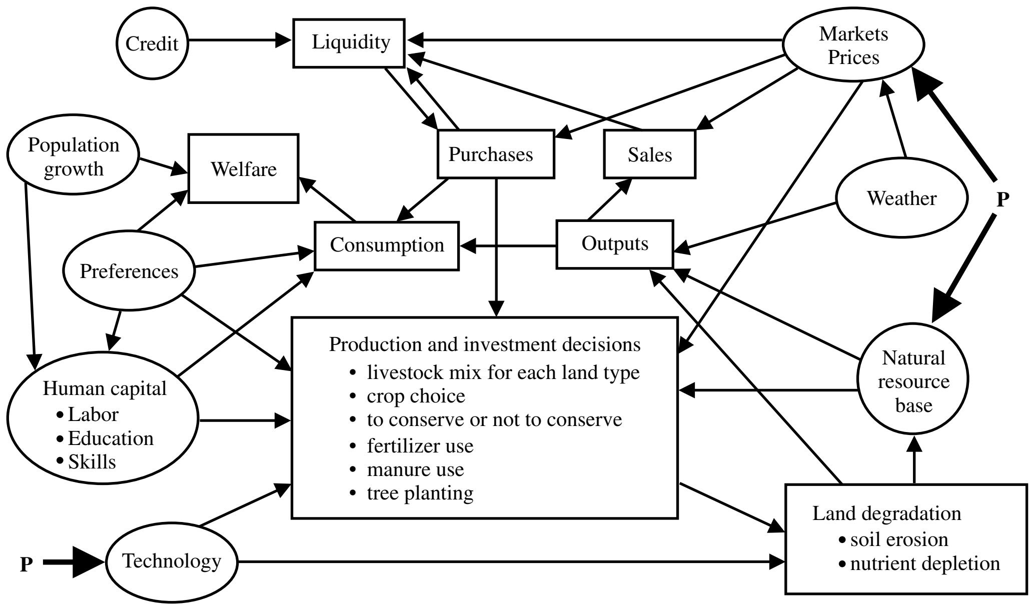
## Model Description

Earlier versions of this model include those of Shiferaw, Holden, and Aune (2000, 2001). The main extensions of the model presented here are the introduction of risk due to stochastic rainfall, a better representation of the market imperfections found in the area, a better calibration of the model to the actual conditions in the area based on new survey data (Holden and Shiferaw 2000), and numerous minor adjustments improving the theoretical consistency of the model and its validity in terms of the model's ability to replicate the current and recent land use and household welfare in the study area.

[6]We focus only on one household group in this report, the dominant land user group, those with two or more oxen.

[7]A dynamic effect that the model does not capture is the beneficial impact of crop rotation, for example, the residual effect of leguminous crops.

**Figure 3.1 Main components of bioeconomic household group model**




We present here the basic theoretical structure of the model. Figure 3.1 gives an illustration of the main elements of the model. **P** in the figure stands for policy interventions that we will come back to later.

The household model represents an average household in a household group, where the households in the study area have been divided into three relatively homogeneous groups based on oxen ownership, as oxen are the most vital privately owned resource. Oxen distribution is more skewed than the land distribution, and the number of oxen is also an important determinant of whether households participate in land rental markets. We leave out the household group subscripts in the exposition below to keep the notation simple.

### Objective Function

Households are assumed to maximize their welfare:

$$U = \sum_{0}^{T} \rho^t u_t \qquad (1)$$

through a time-separable utility function over the time horizon $T$. Utility in period $t$ is discounted by the discount factor,

$$\rho^t = \left(\frac{1}{1+\delta}\right)^t,$$

where $\delta$ is the utility discount rate.[8]

Utility in period $t$ is represented by a constant partial relative risk aversion utility function:

$$u_t = (1-\mu)Y_t^{1-\mu} + \mu - 1, \qquad (2)$$

where $\mu$ is the partial relative risk aversion or absolute value of the elasticity of marginal utility of certainty equivalent full income,[9] $Y_t$, which is equal to

$$Y_i = E(I_t) - \psi_{1t} - \psi_{2t}, \qquad (3)$$

[8]The discount rate was set to vary inversely with the income of households but was in the range 26–29 percent for the simulations with the two-oxen households.

[9]This type of utility function has been used by Binswanger (1980, 1981, 1982) in his empirical study of risk preferences of farmers. It has the advantage that risk aversion can be captured by a single parameter. In most of our

where $E(I_t)$ is normalized expected full income in period $t$, $\psi_{1t}$ is a "downside" risk premium related to obtaining formal credit, and $\psi_{2t}$ is a risk premium related to drought risk in the *belg* season.[10] Full income was normalized by the poverty line full income ($\gamma_t$), while the risk premiums were normalized by the poverty line ($\zeta_t$), excluding value of leisure:

$$E(I_t) = E(y_t)/\gamma_t, \tag{4}$$

where $E(y_t)$ is the expected full income (measured in Ethiopian birr) in period $t$. Subsistence leisure, $Le_{\min}$, is valued at the minimum wage rate, $w_{\gamma t}$, required for the work force of the household, taking out only the subsistence level of leisure, to generate an income exactly equal to the poverty line income:

$$w_{\gamma t} = \zeta_t / L_{\max}, \tag{5}$$

where $L_{\max}$ is the maximum time available for work and $\zeta_t$ is the poverty line income excluding the value of leisure. The time endowment, $F_t$, of the household may then be formulated as follows:

$$F_t = Le_{\min} + L_{\max} \tag{6}$$

and poverty line full income is:

$$\gamma_t = w_{\gamma t} F_t. \tag{7}$$

This formulation gives utility equal to zero if the household has $Y_t = 1$, gives negative utility if $Y_t$ is below the poverty line ($Y_t < 1$), and positive utility if $Y_t > 1$.[11] Population growth[12] affects the time endowment (labor force) and consumer units and thus poverty line income, causing these to grow proportionally over time.

We are interested in the welfare changes of households over time. We define a Boserupian development path (Boserup 1965) as a path where utility, $u_t$, grows over time, and a Malthusian development path (Malthus 1987) as a path where utility declines over time.[13] The requirement for a Boserupian development path is then that income grows faster than the population, since $Y_t$ is a measure of per capita income in period $t$.

The risk premiums are calculated as follows, using a Taylor expansion and approximation over the utility function (Sadoulet and de Janvry 1995):

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simulations we used $\mu = 3$. This was based on a modified method to elicit risk preferences of individual household members, similar to the experimental approach used by Binswanger, but using only hypothetical questions related to choice between staple food crops with different expected outputs and risk and stated probabilities of good and bad (drought) years.

[10]When it comes to the drought and credit risks, they are treated as additively separable risks. There are two rainy seasons per year. Drought occurs during the short *belg* rain season. During a drought it will not rain enough to make it possible for farmers to plant and apply fertilizer. They will always plant in the long rains (*meher* season). The credit risk does not relate to drought but to the risk of hailstorms or frost damaging the crops where fertilizer has been applied (implying no drought).

[11]This implies that we have taken risk into account in the measurement of poverty/welfare of households. We therefore consider a risk-averse person with an uncertain expected income of $I$ poorer than a risk-averse person with a certain income of $I$. This is not yet a common approach but we refer to Cruces and Wodon (2003) for a recent application of this approach to directly incorporate risk into the measurement of income, and therefore poverty.

[12]A population growth rate of 2 percent per year is used. This rate is lower than the average national rate for Ethiopia. We set it lower owing to the high population pressure in the area and the growing food deficit that may lead to more out-migration.

[13]The trend must be evaluated over a period of several years, as short-term disturbances may otherwise cover the trend. The non-stochastic approach chosen allows us to assess the trend and the factors affecting the trend more carefully.

$$\psi_{1t} = \psi_{1t}(\mu, \mu_d, C_{ft}, i, \zeta_t, E(I_t)) = 0.5(\mu + \mu_d)[(C_{ft}(1 + i))^2/\zeta_t]E(I_t) \quad (8)$$

$$\psi_{2t} = \psi_{2t}(\mu, \text{var}(I_t), \zeta_t, I_t) = 0.5[\text{var}(I_t)/\zeta_t]E(I_t), \quad (9)$$

where $\mu_d$ is the additional risk aversion related to credit risk,[14] $C_t$ is the amount of credit taken in period $t$, $i$ is the interest rate, and $\text{var}(I_t)$ is the variance of income. Variance of income is computed on the basis of outcomes in good and bad years (drought years) and the probability of drought. This implies that variance of income also depends on crop choice and land degradation/conservation decisions.

## Market Characteristics

We have the following market characteristics in the models. We leave out the subscript for year to simplify the notation.

*Credit Market.* Formal credit in kind for fertilizer that is constrained from above:

$$p_f Fe = C_f \leq \bar{C}_f, \quad (10)$$

where $p_f$ is the price of fertilizer, $Fe$ is quantity of fertilizer, $C_f$ is credit taken for fertilizer, and $\bar{C}_f$ is the maximum quantity of fertilizer credit that the household can obtain. This credit must be repaid after harvest (seasonal credit only). It may also be possible to obtain informal credit ($C_i$) within the village at a higher rate of interest:

$$C_i \leq \bar{C}_i. \quad (11)$$

This credit must also be paid back within the same year. Holden and Shiferaw (2000) found that 42 percent of the households surveyed in Andit Tid stated that they had access to credit for farm input purchase, while 28 percent stated that they had access to credit for consumption purposes (informal credit).

*Labor Market.* Households are assumed to have constrained access to non-farm employment, and the wage rate in the labor market varies across seasons (observed seasonal variation is included in the model). Households may also hire labor for work on the farm. Hired labor is not a perfect substitute for family labor, however, as there are search, screening, and monitoring costs related to hiring labor (Feder 1985; Sadoulet and de Janvry 1995). Likewise, there are search costs related to finding off-farm employment. A transaction cost related to hiring labor of about 10–20 percent of the wage rate is added to capture this.[15] The household shadow wage, $w_p^*$, should fall between the buying wage ($w_{bp}$) and the selling wage ($w_{sp}$) when households do not participate and are not rationed out of the labor market:

$$w_{sp} \leq w_p^* \leq w_{bp}. \quad (12)$$

Empirical evidence seems to indicate that there are limited off-farm employment opportunities, however, and households may therefore be rationed out of the labor market. This may cause the shadow wage in agriculture to fall below the market wage rate. This is a classical issue in development eco-

[14]Many farmers in the area feared to take credit because of past experiences with repayment problems when crops failed, forcing them to sell their livestock, and there were even reported cases of imprisonment. Unlike in the credit-insurance literature, the credit did not contribute to consumption smoothing in our case study area. This is similar to what Boucher and Carter (2001) have called "risk rationing" where the lenders shift so much contractual risk to the borrowers that they voluntarily withdraw from the credit market. The specification is also in line with the findings in risk preference studies comparing the results of games with gains only with games with gains and losses. People were found to be more risk averse in the latter case (Binswanger and Sillers 1983; Wik et al. 2004).

[15]The width of the price band was kept constant but the wage rates fluctuated seasonally.

nomics that dates back to the Lewis model (Lewis 1954) and the efficiency wage theory (Leibenstein 1957, 1958). There are nutrition-based and learning-based explanations for the failure of the market wage to fall sufficiently to clear the market. We think that the nutrition-based explanation is plausible in Ethiopia. Clark and Haswell (1970, cited in Ray 1998, p. 273) provide estimates of energy requirements for agricultural work (from West Africa) in the range of 213–502 kilocalories per hour of work, showing a clear rationale for a minimum wage. This creates an equilibrium minimum wage through which some individuals are rationed out (involuntary unemployment) because they are not capable of supplying the labor at a lower wage (Ray 1998, p. 493). This is also consistent with the assumption that households are drudgery averse (Chayanov 1966; Nakajima 1986). Based on Nakajima's theory (1986), we have assumed that the shadow wage (reservation wage) is an increasing function of the time worked and that there is a trade-off between income and leisure. Indifference curves between income and leisure will be upward sloping and convex in labor and income space. Household preferences for leisure in income-labor space are formulated as a reservation wage curve that is convex and upward sloping and calibrated (βs in equation [13]) to fit the observed seasonal labor supply/leisure demand and wage rates in the area, and does not fall below a minimum level:

$$w_p^* = \beta_1 + \beta_2 D_p + \beta_3 (D_p - \beta_4)^2 \quad (13a)$$

$$D_p = L_p^* / W \quad (13b)$$

$$L_p^* \leq \bar{L}_p \quad (13c)$$

$$L_p^* = L_{pF} - L_{pH} + L_{pO} \quad (13d)$$

$$L_{pF} = L_{pC} + L_{pL} \quad (13e)$$

$$L_{pT} = L_p^* + L_{pE}, \quad (13f)$$

where βs are parameters, $D_p$ is the seasonal family labor divided by the household labor force ($W$), $L_p$ is the maximum seasonal time that is available for work,[16] $L_{pC}$ is seasonal labor in crop production, $L_{pL}$ is seasonal labor in livestock production, $L_{pO}$ is seasonal off-farm family labor, $L_p^*$ is total seasonal family labor, $L_{pF}$ is total seasonal on-farm labor, $L_{pH}$ is hired-in labor, $L_{pT}$ is the total seasonal time endowment, and $L_{pE}$ is the seasonal leisure time. Labor for conservation (building of new structures, maintenance of structures, and removal of old structures) is included in $L_{pC}$. Seasonal nonfarm family labor may be constrained or unconstrained (alternative simulations) but it can take place in any season of the year. Seasonal access to food-for-work (FFW) employment was also included in some simulations.

*Land Market.* There is an informal rental market for land in the area. This market is interlinked with the output market as the rent is paid in form of a share of the output (share tenancy). It is typically households without oxen that are forced to rent out part of their land to households with two or more oxen. The scarcity of land in the area, in combination with the stickiness of the "price" in form of share of the output, causes demand (denoted by superscript $d$) for land to exceed supply (Holden and Shiferaw 2000). A good reputation is important to be able to rent in land. For households renting in land, denoted by superscript 2, we get

$$A_{qo}^2 = \bar{A}_{qw}^2 + A_{qr}^2 \quad (14a)$$

$$A_{qr}^{2d} > \Lambda A_{qr}^{0s} | \bar{\alpha}_q \quad (14b)$$

[16]Maximum time available for farm work is determined by subtracting religious holidays from the total number of days in the period. Work on the farm is not permitted on religious holidays.

$$A^2_{qr} \leq \Lambda A^{0s}_{qr} | \bar{\alpha}_q, \quad (14c)$$

where $A^2_{qo}$ is a vector of operated land holding (subscript $o$) by land type (subscript $q$); $\bar{A}_{qw}$ is a vector of owned land (subscript $w$) by land quality class; and $A^2_{qr}$ is land rented in (subscript $r$ is for rented land), which is supply constrained given the shares of the output, ($\bar{\alpha}_q$), that have to be paid to the owner. Typically, these shares were equal to 0.5 for the best-quality land, 0.33 for the medium-quality land, and 0.25 for poor-quality land. There was excess demand ($A^{2d}_{qr}$) for each of these shares. $\Lambda$ is the relative population weight for households renting out versus households renting in land. For households renting out land, denoted by superscript 0, we have:

$$A^0_{qo} = \bar{A}^0_{qw} - A^{0s}_{qr} | \bar{\alpha}_q. \quad (15)$$

The third constraint in equation (14) will therefore bind as area demanded exceeds supply in the second constraint in equation (14). In the version of the model that is presented in this report we include only the two-oxen households and impose constraints on their access to land to rent in, based on observed access.

*Oxen Rental Market.* Households that rent out land do so because they lack oxen and are unable to borrow or rent in oxen to cultivate the land themselves. Oxen owners are reluctant to rent out their oxen owing to moral hazard problems and the risk of their oxen being mismanaged. Oxen may be borrowed or rented ($Ox_{rP}$), from relatives or close neighbors, usually in exchange for labor ($L_{lop}$) (interlinked markets).[17] Access to oxen in this way may be constrained as indicated in the equation (16b). Seasonal oxen working days ($Ox_{op}$) is therefore the sum of the working days by owned oxen ($Ox_{wp}$) and the amount of oxen days rented in or out during the period. Oxen labor days from owned oxen is limited by the number of religious holidays in the month:

$$Ox_{op} = Ox_{wp} \pm Ox_{rp} \quad (16a)$$

$$w_{lo} L_{lop} = Ox_{rp} \leq \bar{O}x_{rp} \quad (16b)$$

$$Ox_{wp} \leq \bar{O}x_{wp}. \quad (16c)$$

The cost of keeping oxen relates to their purchasing or breeding cost, fodder demand, and the labor cost of looking after them.

*Fodder Market.* Fodder is supplied by crop residues, grass production on grazing land and fallow land, and purchased fodder. Households may decide to buy or sell fodder depending on their farm size, land allocation choices, the size of their livestock, and the price and availability of fodder. The supply of fodder ($Fo$) in dry matter through own production and purchase ($Fo^d$) is

$$Fo = \kappa\theta yi_{CrAq} A_{Cr} + \kappa Fo^d | P_{fo} \quad (17)$$

$$Fo^d \leq \bar{F}o,$$

where $\theta yi_{CrAq}$ is a vector of crop residues or fodder yields for different crops, including grass and fallow land, for different land types, and $\kappa$ is a vector of dry matter conversion factors. Land scarcity appeared to cause fodder scarcity in the area, as households appeared to have incentives to keep more animals than they could feed well throughout the year. We therefore imposed a fodder supply constraint in the model ($\bar{F}o$).

*Seeds Market.* It is assumed that markets for seeds function well but a price band is included, making the price of purchased seeds 5 percent higher than the selling price for seeds. Households also have the option of storing seeds from their own harvest for the next season.

[17]Usually 2 man-days of labor are required for 1 day of work with a pair of oxen.

*Output Markets.* Output markets are assumed to function well, but a price band is included such that the purchase price is assumed to be 5 percent higher than the selling price.

### Land Degradation and Conservation

The main forms of land degradation in the model are in the form of soil erosion and soil nutrient depletion. Plot-level soil erosion per unit of land ($se_{Aq}$) is a function of soil type, soil depth and slope (land type class, $Aq$), rainfall ($\psi_r$), crop choice ($Cr$), and use of conservation technology ($\Psi$):

$$se_{Aq} = se(A_q,\ \psi_r,\ Cr;\ \Psi). \tag{18}$$

Soil erosion rates were determined based on field experiments carried out by the Soil Conservation Research Program (SCRP) in the study area.[18] Farmers may influence soil erosion rates through their crop choice/land use or by building or removing conservation technologies on the different types of land. The model implicitly evaluates the profitability of erosion control on the different types of land, for example, on regosols versus andosols, on shallow soils versus deep soils, and on very steep land versus less steep land. Soil erosion affects soil depth ($sd$) through a transition equation (leaving out the land type subscript):

$$sd_t = sd_{t-1} - \tau se_t, \tag{19}$$

where $\tau$ is a conversion factor. Nutrient depletion in the model focuses on the nutrients nitrogen and phosphorus, which are considered to be the main nutrients limiting crop production in the area. The balance or depletion per unit of land at plot level depends on the land/soil type, the stock of nutrients in the soil, crop choice, conservation technology use, yield, application of fertilizer and manure, and the release of nutrients from the soil.[19] Nutrients are also lost through eroded soil, and this soil is richer in nutrients than the soil remaining behind.[20] Release of nitrogen from the soil is assumed to depend on the stock of nitrogen.[21] The change in nitrogen stock is given by

$$N_{t+1} = N_t - \varphi(N_t - \eta(se_t)) - \eta(se_t), \tag{20}$$

where $N$ is nitrogen stock, $\varphi$ is the share of nitrogen mineralized in each period, and $\eta$ is the nitrogen composition of the soil.[22] The

[18]It may be questioned whether the erosion experiments captured the inflow of soils and not only the outflow, that is, whether soil accumulation may have occurred somewhere in the watershed. Conservation structures definitely captured much of the eroded soils, and this was likely to have a positive impact on crop yields. The topography was such that it did not allow much soil accumulation in the valley bottoms that could benefit crop production. The model is calibrated based on erosion, conservation technology, and yield experiments on different soil types and slope classes over several years. These experiments should also capture much of the spatial movement of soils. We cannot claim that these experiments provide unbiased estimates but it is the best scientific information available. Soil formation, which typically is very low compared to the erosion rates, is also ignored. Spatial externality effects may be underestimated, but may, however, be either positive or negative in terms of how they affect crop yields. They may, for example, contribute to gully formation and sediment accumulation, which negatively affect yields.

[19]Manure enters the production function only in form of nutrients and is therefore a substitute for fertilizer. Its additional effects on soil structure, infiltration, and moisture holding capacity may cause manure to be complementary to fertilizer, however. More research is required to provide good data on this effect.

[20]An enrichment factor of 2 is used for nitrogen.

[21]We assume that 1 percent of the nitrogen stock is released each year (Shiferaw et al. 2000).

[22]This assumes that all fertilizer nitrogen applied is lost and does not accumulate in the system. Fertilizer use contributes to fodder production that again may lead to an increase in livestock and manure production, and this may have a positive impact on crop productivity in subsequent years.

change in plant available nitrogen from period to period ($\phi$) due to nutrient depletion is computed as

$$\phi = \varphi(N_t - N_{t-1}). \quad (21)$$

This reduction in plant available nitrogen is included into the production function (equation [24]). The nutrients in animal manure are released over 2 years, with 60 percent being released in the first year and the rest in the following year and contribute to the overall nutrient supply for crop production together with fertilizer nitrogen:

$$N_F = \lambda Fe + 0.6\vartheta Ma_t + 0.4\vartheta Ma_{t-1}, \quad (22)$$

where $\lambda$ is the nitrogen content of fertilizer, *Ma* is manure, and $\vartheta$ is nitrogen content in manure. The effects of nitrogen and rooting depth depletion on yields are therefore included while the effect of phosphorus depletion is not included because incorporation of this effect requires additional data on phosphorus fixation, conversion of stabile phosphorus to labile phosphorus, and the total phosphorus stock in the soil.

Households may decide to conserve their land by introducing conservation structures (graded soil/stone bunds). Only labor is needed as an input for this, 100–120 working days per hectare, depending on the slope of the land. Maintenance of the structures requires an additional 15–20 working days per year per hectare. Households may also decide to remove conservation structures, and this is estimated to require only 25 percent of the time required for construction. The conservation structures may occupy some productive land, thereby reducing the effective cropping area, which may reduce initial crop yields (Shiferaw, Holden, and Aune 2000). Two formulations of the model are used here: (1) one in which the yield loss is negligible and (2) one in which initial yields are reduced by 5–10 percent depending on the slope of the land. Building or removing conservation structures may therefore affect long-term as well as short-term yields.[23] The long-term yields are affected by the impact on land degradation (soil erosion and nutrient depletion) and the feedback through crop yields.

### Crop Production

Yields for the different crops are functions of soil type, soil depth, slope, application of fertilizer and manure converted into nitrogen and phosphorus, and conservation technology ($\Psi$). The intercept of the yield ($yi_{\text{int}}$) in the yield ($yi$) function, suppressing the crop type and year, is a function of soil type ($A_q$) and soil depth ($sd$):

$$yi_{\text{int}} = yi(A_q, sd), \quad (23)$$

and the yield by soil type is

$$yi_{Aq} = yi(yi_{\text{int}}, \Psi, N_F, \phi, P_F), \quad (24)$$

where $N_F$ is fertilizer and manure nitrogen added, $\phi$ is the change in available mineralized nitrogen,[24] and $P_F$ is phosphorus added through fertilizers and manure. Yields may be influenced by conservation technologies ($\Psi$) as conservation structures take up some part of the land; may harbor pests; and may reduce runoff, leaching, and, of course, erosion. The short-term effect on yields of the use of conservation technologies is therefore ambiguous, but over time yields under conservation should decline less rapidly than without conservation. More information on this can be found in Shiferaw and Holden (2001).

[23]Conservation structures may also increase short-term yields in some cases because of a moisture conservation effect or better protection in case of excess rainfall.

[24]This term comes in as a reduction in the stock of nitrogen that is mineralized and therefore available for plant growth. This reduction reduces productivity over time.

The formulation implies that fertilizer and conservation technologies are substitutes in production as fertilizer may be used to compensate for lost nutrients through erosion when conservation technologies are not used. There may also be complementary effects of combining fertilizer and conservation technologies as conservation technologies may improve fertilizer utilization. We have no experimental or other data from the study area, however, that can help us to quantify this effect.

Crop choice will depend on the profitability (prices and yields), food, fodder, security, labor demand and distribution, the suitability of the different types of land, access to inputs such as traction power and fertilizer, and the property right to or rental arrangement for the land. The crops grown in the area include barley, wheat, field pea, horse bean, lentil, and linseed. Land may also be planted with eucalyptus trees or grass or left fallow. All the crops may be grown in the *meher* (main rainy) season but only barley, field peas, and lentils are grown in the *belg* (small rainy) season.

## Livestock Production

Cattle, sheep, goats, equines, and chicken are the common livestock types in the area. All these, except equines, are included in the model. The productivity of the livestock, birth rates, mortality, feed requirements, milk production, plowing capacity, manure production, culling rates, and labor and other input costs were included. For example, cattle are divided into male and female calves, bulls, heifers, cows, and oxen. The models are calibrated to the average livestock holding for the different household groups (with the groups representing households owning no, one, or two oxen), to the productivity and lifetime of the local breeds of livestock. To simplify the model solution, the number of animals in each category is treated as a continuous number, not an integer.[25] This applies to rearing, purchase, slaughter, and sale of animals. Adult animals kept in a specific period are computed as

$$LVP_{t+1} = (1 - \varsigma - m)LVP_t + LVB_{t+1} + LCR_t - LVS_{t+1}, \quad (25)$$

where $LVP$ is animals kept in production, $\varsigma$ is culling rate, $m$ is mortality rate, $LVB$ is animals bought, $LVR$ is young animals reared into adult animals, and $LVS$ is animals sold. Production of young animals is computed as

$$bLVP_{ft} = LVR_t + LVRC_t + LVRS_t, \quad (26)$$

where $b$ is the birth rate, $LVP_f$ are female animals in reproductive age, $LVRC$ is young animals consumed, and $LVRS$ is young animals sold. These equations are adjusted for different animal types depending on the time required in different age classes and their reproduction characteristics (determined from survey data and literature).

The decision to buy or sell animals may depend on livestock productivity, mortality rates, buying and selling prices, fodder availability, cash constraints, food requirements and preferences, and other costs and benefits related to keeping of animals. To avoid complete disinvestments at the terminal year, the model is constrained to such that not more than 20 percent of the stock can be sold in the terminal year.

## Crop–Livestock Interactions

Livestock provide traction power and manure for crop production. A large share of the animal manure from cattle is used for fuel, reducing the amount available for crop production. Crop residues, on the other hand, are an important source of animal fodder. Stover yields are modeled to be a function

[25]This may result in the model predicting more livestock investment or disinvestments than occurs in reality, because of the indivisibility of livestock investment (especially cattle) and cash or credit constraints that likely inhibit such investment.

of crop type and crop grain yields. Crop choice; crop management, for example, use of fertilizer and animal manure; and land degradation therefore also indirectly affect fodder yields. Total fodder production and purchased feeds must satisfy the livestock dry matter feed requirements:

$$Fo = \kappa\theta yi_{CrAq}Aq + \kappa Fo^{d} \geq \xi LVP, \quad (27)$$

where $\xi$ is a vector of dry matter requirements for different types of animals and $LVP$ is a vector of animals kept of different types and age classes. Animal manure available for crop production is calculated as

$$Ma = \varepsilon LVP, \quad (28)$$

where $\varepsilon$ is a vector of the farmyard manure production per animal by animal type that is utilized as farmyard manure (excluding the part used for fuel).

## Household Consumption

An extended quadratic expenditure system, including consumption of food grains, pulses, other consumption, and farm input expenditure, was estimated based on consumption data from the 1994 household survey. The quadratic expenditure system gave a better fit than alternative expenditure systems (linear, log-lin, lin-log). The results of the estimation are presented in Table 3.1. This system does not satisfy exact aggregation. Only the food grain and input expenditure equations were included in the model. The food consumption equations follow:

$$p_gX_g = a_1 + a_2E(I) + a_3E(I)^2 \quad (29a)$$

$$X_g = XP_g + XB_g + XS_g \quad (29b)$$

$$X_g \geq X_{g\min} \quad (29c)$$

$$nuX_g \geq Nu_{\min}, \quad (29d)$$

where $P_g$ is a vector of food prices; $X_g$ is a vector of foods consumed; $a_1$, $a_2$, $a_3$ are expenditure system parameters; $XP_g$ is own production retained for consumption (net of sold and stored seeds) of the commodities; $XB_g$ is purchased consumption; and $XS_g$ is stored produce from the previous period which is consumed during a given period. The last two equations include the additional food preference and minimum energy, fat, and protein requirement equations. Although we have suppressed the time subscripts in these equations, it is important to remember that population growth affects the number of consumers in the household and therefore the minimum food requirement that grows proportionally with population growth.

## Full Income and Cash Constraints

The expected full income is the sum of expected crop and livestock production values less input costs, off-farm income, and the value of leisure:

$$\begin{aligned} E(I) = {} & \Phi p^e_{CB} yi^e_{CrAqB} Aq \\ & + (1 - \Phi) p^e_{CG} yi^e_{CrAqG} Aq \\ & - p_{qc} Q_c + (\Phi p^e_{LB} \\ & + (1 - \Phi) p^e_{LG}) yi_L LVP \\ & - p_{qL} Q_L + w_{po} OF + w^*_p Le, \end{aligned} \quad (30)$$

where $p^e_C$ and $p^e_L$ are vectors of expected prices[26] for crop and livestock[27] production, with the subscripts $B$ and $G$ indicating drought and non-drought years, $yi^e_{CrAq}$ is expected yield by crop and land type, $\Phi$ is the probability of drought, $p_{qc}$ and $p_{qL}$ are prices

[26]The expected prices and expected quantities depend on the state of nature and the probability of drought (weighted prices).

[27]The loss in livestock wealth in drought years is captured through the livestock price in the model that largely may be due to poorer quality animals being brought to the market (lower weight, less meat relative to bones) (McCarthy, personal communication).

**Table 3.1 Results of the quadratic expenditure system used in the model: Seemingly unrelated regression**

| Equation | Observations | Parameters | RMSE | $R^2$ | $\chi^2$ | $P$ |
|---|---|---|---|---|---|---|
| Barley | 80 | 4 | 287.4327 | 0.7871 | 305.9059 | 0.0000 |
| Wheat | 80 | 4 | 118.3131 | 0.3052 | 34.57677 | 0.0000 |
| Horse bean | 80 | 1 | 205.8389 | 0.4514 | 65.81973 | 0.0000 |
| Other food crops | 80 | 4 | 197.1642 | 0.6918 | 181.5386 | 0.0000 |
| Clothing | 80 | 2 | 114.5194 | 0.5064 | 81.51062 | 0.0000 |
| Input expenditure | 80 | 2 | 128.7285 | 0.5794 | 113.8921 | 0.0000 |

| | Coefficient | Standard error | $z$ | $P > \|z\|$ | 95% Confidence interval | |
|---|---|---|---|---|---|---|
| Barley | | | | | | |
| Total expenditure | .1079257 | .0719653 | 1.500 | 0.134 | –.0331238 | .2489752 |
| Total expenditure² | .000034 | $9.16 \times 10^{-6}$ | 3.717 | 0.000 | .0000161 | .000052 |
| No oxen | –332.9857 | 92.70149 | –3.592 | 0.000 | –514.6773 | –151.2941 |
| One ox | –160.5215 | 63.2709 | –2.537 | 0.011 | –284.5302 | –36.51283 |
| Intercept | 553.0011 | 130.9527 | 4.223 | 0.000 | 296.3385 | 809.6637 |
| Wheat | | | | | | |
| Total expenditure | .1358267 | .0322582 | 4.211 | 0.000 | .0726017 | .1990516 |
| Total expenditure² | –.0000115 | $4.10 \times 10^{-6}$ | –2.812 | 0.005 | –.0000196 | $-3.50 \times 10^{-6}$ |
| No oxen | 181.2548 | 45.67324 | 3.969 | 0.000 | 91.73689 | 270.7727 |
| One ox | 50.71345 | 31.21271 | 1.625 | 0.104 | –10.46234 | 111.8892 |
| Intercept | –203.0583 | 59.43661 | –3.416 | 0.001 | –319.5519 | –86.56472 |
| Horse bean | | | | | | |
| Total expenditure | .1342121 | .016543 | 8.113 | 0.000 | .1017885 | .1666357 |
| Intercept | –102.0223 | 46.891 | –2.176 | 0.030 | 193.927 | –10.11764 |
| Other food crops | | | | | | |
| Total expenditure | .3413225 | .0503891 | 6.774 | 0.000 | .2425616 | .4400833 |
| Total expenditure² | –.000016 | $6.36 \times 10^{-6}$ | –2.521 | 0.012 | –.0000285 | $-3.57 \times 10^{-6}$ |
| No oxen | 126.8391 | 71.71962 | 1.769 | 0.077 | –13.72878 | 267.407 |
| One ox | 110.5144 | 48.98375 | 2.256 | 0.024 | 14.50798 | 206.5208 |
| Intercept | –237.3885 | 93.99712 | –2.525 | 0.012 | –421.6194 | –53.15749 |
| Clothing | | | | | | |
| Total expenditure | .1448116 | .0282768 | 5.121 | 0.000 | .08939 | .2002331 |
| Total expenditure² | $-9.12 \times 10^{-6}$ | $3.76 \times 10^{-6}$ | –2.423 | 0.015 | –.0000165 | $-1.74 \times 10^{-6}$ |
| Intercept | –111.0048 | 44.28079 | –2.507 | 0.012 | –197.7936 | –24.2161 |
| Input expenditure | | | | | | |
| Total expenditure | .1032091 | .0103822 | 9.941 | 0.000 | .0828604 | .1235579 |
| Labor units | 7.775533 | 5.192651 | 1.497 | 0.134 | –2.401875 | 17.95294 |
| Intercept | 37.41215 | 30.63557 | 1.221 | 0.222 | –22.63247 | 97.45677 |

Note: Base group in the estimations: households with two oxen.

of inputs in crop and livestock production, $Q_C$ and $Q_L$ are vectors of non-labor input quantities in crop and livestock production, $w_{po}$ is a vector of seasonal wage rates in off-farm employment, and $OF$ is a vector of seasonal participation in the labor market.

The cash constraint for farm input purchase is derived from the extended quadratic expenditure system. The quadratic term was insignificant and was therefore left out (Table 3.1).

## CHAPTER 4

# Methodology

### Data and Calibration

The site selected for this study is unique in the African context when it comes to the level of detail of biophysical and socioeconomic data available over a period of 15–20 years. The biophysical data include:

- Detailed soil physical and chemical data
- Erosion data at plot level for different conservation technologies and crops over several years (from researcher- and farmer-managed experiments and farmers' plots)
- Crop yield data on different soils and under different conservation technologies
- Climatic data
- Detailed plot-level data from a stratified random sample of 120 households

Plot-level data were collected by visiting and measuring (by triangulation) and observing all plots and by interviewing the households owning or renting the plots. Table 4.1 summarizes the plot-level data by soil/climatic zone and soil depth.

Erosion rates were estimated based on experiments carried out by the Soil Conservation Research Program (SCRP) over many years in the study site. Yield responses were estimated based on SCRP experimental data for conservation technology responses, and based on Food and Agriculture Organization (FAO) fertilizer experiments and local crop-fertilizer demonstration plots managed by the extension system. A more comprehensive analysis of some of these data is presented in Shiferaw and Holden (2001).

Socioeconomic data were collected in household surveys in 1986, 1994, 1998, and 2000. These data were used to structure and calibrate the bioeconomic models for the different household categories (Tables 4.1–4.3). Survey methods and sample sizes changed (improved) over time, limiting the possibility for panel data analysis. Farm plots were measured (triangulation method) only in the last survey and it was found that measured plot sizes often deviated considerably from farmers' own stated farm sizes and official farm sizes used in the land redistribution allocation. On average farm plots were found to be almost 30 percent larger than official plot size but there was a large amount of variation in both directions. The models presented here were calibrated to measured plot and farm sizes.

Price data were collected in the area during our surveys both at household level and in the local markets. Prices from 1997 (normal year) and 1999 (drought year) (Table 4.4) were used to construct expected incomes based on the probability of drought year and expected prices and expected outputs in drought years and years without drought.

**Table 4.1 Farm areas by zone and slope class in Andit Tid, 2000**

| Land type | Depth class (cm) | Total area (measured) (ha) | Percentage of land type area |
|---|---|---|---|
| *Dega* | <30 | 210 | 24.9 |
| | 30–60 | 432.6 | 51.3 |
| | >60 | 200.9 | 23.8 |
| *Wurch* | <30 | 43.6 | 17.7 |
| | 30–60 | 94.2 | 38.3 |
| | >60 | 107.8 | 43.9 |
| All | <30 | 253.6 | 21.4 |
| | 30–60 | 526.8 | 48.1 |
| | >60 | 308.8 | 30.5 |

## Unit of Analysis

Holden, Shiferaw, and Pender (2001) found that plot-level land use depends on oxen ownership, signifying the imperfections in land and oxen rental markets. Oxen ownership is also an important determinant of land rental market participation. Households without oxen typically rent out part or all of their land. Households with two oxen or more are the ones renting in land. Households with one ox typically share oxen with other one-ox households, as a pair of oxen is needed for plowing. Shiferaw and Holden (1998) found, based on econometric analysis of plot-level data collected in 1994, that poor and land-scarce households were more likely to dismantle conservation structures introduced through FFW in the early 1980s. These findings indicate that bioeconomic models at watershed and/or community levels fail to address issues related to social differentiation when it comes to its impact on land use. Watershed or community level bioeconomic models typically rely on perfect market assumptions and separability of production decisions from consumption decisions or on lack of externalities related to interactions among agents. These assumptions do not fit well with the empirical reality in the Ethiopian highlands in general and the case study area in particular. It appears more appropriate to model land-use decisions at household group level, and aggregate from household group to the community or watershed level afterwards.

Household group modeling and aggregation requires proper weighting and calibration of the different models to satisfy local demand and supply equations. It is assumed that population growth takes place by growth of average household size for the different household groups. The share of households

**Table 4.2 Changes in Andit Tid, 1986–99**

| Variable | 1986 | 1999 |
|---|---|---|
| Average farm size | 3.77 ha | 2.16 ha |
| Average household size | 5.04 | 5.67 |
| Average oxen holding | 1.54 | 1.2 |
| Average number of cows | 1.18 | 0.8 |
| Average number of sheep | 6.25 | 5.3 |
| Cereal production | Net sellers | Net buyers |
| Tropical livestock units (TLU)/ha | 1.48 | 1.71 |

**Table 4.3 Basic household and farm characteristics for household groups in 1999, used as input in the model**

| | Household group | | |
|---|---|---|---|
| Variable | Two or more oxen | One ox | No oxen |
| Household size | 6.44 | 5.81 | 4.1 |
| Work force | 3.53 | 2.89 | 2.2 |
| Consumer units | 5.15 | 4.54 | 3.31 |
| Land owned by land type (ha) | | | |
| Regosols, slope 0–20%, depth 25 cm | 0.79 | 0.69 | 0.5 |
| Regosols, slope 0–20%, depth 45 cm | 0.41 | 0.36 | 0.26 |
| Regosols, slope 0–20%, depth 60 cm | 0.15 | 0.13 | 0.1 |
| Regosols, slope >20%, depth 25 cm | 0.35 | 0.31 | 0.22 |
| Andosols, slope 0–20%, depth 25 cm | 0.44 | 0.39 | 0.28 |
| Andosols, slope 0–20%, depth 45 cm | 0.27 | 0.24 | 0.17 |
| Andosols, slope 0–20%, depth 60 cm | 0.15 | 0.14 | 0.1 |
| Andosols, slope >20%, depth 25 cm | 0.12 | 0.1 | 0.07 |
| Total farm size (ha) | 2.68 | 2.36 | 1.7 |
| Livestock ownership | | | |
| Oxen | 2 | 1 | 0 |
| Cows | 1 | 0.69 | 0.5 |
| Bulls | 0.38 | 0.34 | 0.2 |
| Heifers | 0.58 | 0.21 | 0.1 |
| Sheep, ewes | 3.71 | 2.63 | 1.07 |
| Sheep, rams | 1.63 | 0.82 | 0.07 |
| Goats, does | 0.77 | 0.32 | 0.07 |
| Goats, bucks | 0.29 | 0.13 | 0 |
| Hens | 2 | 2 | 2 |

in the different household groups may change over time, however, and this must be adjusted during aggregation in later years. Alternatively, farm sizes could have been adjusted down if fragmentation of landholdings through land redistribution continues. We have calibrated the models to fit the actual land sizes after the latest land redistribution in 1997 in the study area. Farm sizes are based on actually measured plots. Measured farm sizes turned out to be on average as much as 30 percent larger than stated farm sizes by farmers.

The simulations presented in this report include only the largest of the household groups, the one with two or more oxen. This household group farms about 70 percent of the land in the area and therefore represents the principal land managers. The household group without oxen largely rent out their land to this household group. Families in the third household group, those with one ox, typically depend on cooperation with another household with one ox, in order to pair their oxen for cultivation. We have therefore taken the interaction issues between these household groups as exogenous in our modeling effort on the dominant household group. This implies that we have not been able to capture endogenous village prices that are exogenous to households. We have treated such prices as exogenous or in the land rental market assuming that payment is a fixed share of output (typical sharecropping contract) while access to such land is supply constrained. Holden and Lofgren (2004) give an example of a model that captures such interactions among household

**Table 4.4 Prices of crops and livestock in 1997 (normal year) and 1999 (drought year) (Ethiopian birr)**

| Crop or livestock type | Price 1997 | Price 1999 |
|---|---|---|
| Barley, *meher* (per kg) | 1.05 | 1.65 |
| Barley, *belg* (per kg) | 0.83 | 1.42 |
| Wheat (per kg) | 1.66 | 2.35 |
| Field pea, *meher* (per kg) | 2.15 | 2.37 |
| Field pea, *belg* (per kg) | 2.15 | 2.08 |
| Horse bean (per kg) | 1.67 | 2.38 |
| Lentil, *meher* (per kg) | 2.41 | 3.66 |
| Lentil, *belg* (per kg) | 2.41 | 3.75 |
| Linseed (per kg) | 1.66 | 3 |
| Oxen (per head) | 966 | 585 |
| Cows (per head) | 558 | 460 |
| Bulls (per head) | 500 | 293 |
| Heifers (per head) | 333 | 237 |
| Calves (per head) | 172 | 68 |
| Sheep, ewes (per head) | 57 | 41 |
| Sheep, rams (per head) | 45 | 56 |
| Lambs (per head) | 33 | 50 |
| Goats, does (per head) | 46 | 41 |
| Goats, bucks (per head) | 48 | 54 |
| Kids (per head) | 33 | 40 |
| Hens, chicken (per head) | 10 | 7 |

groups endogenously. Such a model requires a village social accounting matrix as a starting point and it is less detailed when it comes to agro-ecosystem specifications and dynamic effects. Shiferaw and Holden (2004) use another version of the model presented here and include simulations for the household group without oxen.

## Choice of Time Horizon and Seasonality in the Model

The simulations presented in this report include models with 5- and 10-year time horizons. The time required for each model to produce a solution increases rapidly as the time horizon is increased. The probability that the model does not solve also increases with the time horizon. This was particularly the case when we introduced risk in the model and increased the probability of drought. It also became harder to make the models solve for the household groups with one or no oxen. This is the main reason why we do not include simulations for those household groups in this report. The logic behind these modeling difficulties has to do with the problem of solving large nonlinear models that are nonlinear both in the objective function and in the constraints. At the same time we try to model households that live very close to their subsistence level of income and that are pushed toward even lower levels of income by population growth and land degradation. This increases very much the probability that the models become infeasible as the number of years for which the models are solved is increased. A great deal of time was spent to ensure good starting values for the models, and the specific choice of utility function (allowing negative utility and incomes below the poverty line) helped to reduce the problems faced.

We refer to Holden (2004) for a discussion of alternative bioeconomic modeling approaches. A good alternative way to the approach chosen here could be the recursive dynamic modeling approach that Barbier (1996, 1998) and Barbier and Bergeron (1998, 1999, 2001) have used in Burkina Faso, Peru, and Honduras. They used a 3- or 5-year planning horizon for each optimization but ran the model recursively by restarting the model using only the first-year results for each solution. In this way, they were able to run simulations for much longer time periods (20–100 years). They were also able to introduce shocks in the model. This approach was seriously considered and even attempted, but found to be very difficult to implement given the complexity of the dynamic and other aspects of our model. It was therefore discarded for practical reasons.

Discounting of utility was captured through the time-separable utility function. The discount rate was endogenous in the model and dependent on household income per consumer in the household. Discount rates were estimated by asking households hypothetical questions to identify their indifference points between receiving a fixed amount in the future and a variable amount

**Table 4.5 Cropped areas in 1999 and predicted ranges of cropped areas over 5 years (ha)**

| Crop | Household group (number of oxen owned) | | | Two-oxen household group model: Predicted areas (range over 5 years) | |
|---|---|---|---|---|---|
| | 0 | 1 | 2 | Credit constrained | Credit unconstrained |
| *Meher* season | | | | | |
| Cereals | 0.55 | 0.73 | 0.96 | 0.19–0.79 | 0.25–0.78 |
| Legumes | 0.23 | 0.29 | 0.32 | 0.21–0.45 | 0.23–0.67 |
| Grazing/grass | 0.11 | 0.2 | 0.22 | 0.05–0.57 | 0.00–0.48 |
| Fallow | 0.78 | 0.91 | 1.12 | 0.52–0.54 | 0.35–1.46 |
| Eucalyptus | 0.01 | 0.05 | 0.08 | — | — |
| Degraded | 0 | 0.01 | 0.03 | — | — |
| *Belg* season[a] | | | | | |
| Cereals | — | — | — | 0.60–0.73 | 0.62–0.77 |
| Legumes | — | — | — | 0.13–0.36 | 0.13–0.38 |

[a]1999 was a year with drought in the *belg* season; therefore no crops were planted in this season. This may have caused the shift in barley production to the *meher* season.

at the present time.[28] The discount rates in the model typically were in the range of 26–28 percent for the two-oxen household models presented in this report.

Seasonality was captured in the model by dividing each year into 10 periods. Each of these periods was one month, except the period from March to May, which was a three-month period (slack season). It was the seasonal variation in labor demand and labor supply and the consequent seasonal wage rates that were captured in this way. Each agricultural production activity had a specific seasonal labor demand pattern. The household size and religious holidays limited the availability of household labor. Access to off-farm employment (at seasonal exogenous wages) was constrained in some model simulations and unconstrained in other simulations (simulating better market access). The constraint on such employment was an overall constraint. Access to food-for-work (FFW), on the other hand, was introduced in the slack season (March to May) only to minimize its competition with agricultural production activities.

## Model Validation

The model is validated by comparison of base runs with actual survey data for key output variables for the different household group categories. Table 4.5 shows the actual cropping pattern in the 1999 *meher* season and the predicted cropping pattern for the two-oxen household group (range of areas over 5 years). The year 1999 was a drought year in which no crops were grown in the *belg* season, and this may also have affected the cropping pattern in the *meher* season (more barley production).

The models are constructed in the General Algebraic Modelling System (GAMS). A 5-year model contains about 39,600 variables and 23,300 equations, many of which are nonlinear.

For an assessment of how the seasonality and labor allocation in the model works, an example output for a 5-year model is provided in Appendix B. It illustrates clearly that the shadow wage rates vary systematically across seasons but also change over time.

[28]See Holden, Shiferaw, and Wik (1998) for details about this approach.

# CHAPTER 5

# Results and Discussion

## Land Degradation, Crop Productivity, and Impact of Conservation Technologies

Table 5.1 shows the yield trends over 5 years of barley on regosols (different soil depths and slopes) with and without conservation technologies when no fertilizer or manure is applied. Yields are shown for the cases when conservation structures reduce initial yields and when initial yields are not affected. We see that yields are lowest and decline most rapidly on shallow soils.

In Table 5.2 the decline in yields of barley over a 5-year period on regosols in the *meher* season and on andosols in the *belg* season, with and without conservation technologies, without and with a fairly high level of fertilizer application, are shown. We see that yields decline faster on andosols than on regosols, faster on unconserved than on conserved land, faster on shallow soils and steep slopes, and faster when no fertilizer is used. Yields are declining even on deeper soils that are conserved and receive a high level of fertilizer (55 kilograms of nitrogen and 50 kilograms of phosphorus pentoxide per hectare) because conservation does not eliminate soil erosion and a marginal reduction in rooting depth reduces yields. The impact of conservation technologies on yields (without fertilizer use) on different slopes and soil depths for regosols is presented in Figure 5.1. The impacts of conservation technologies and fertilizer (separately and in combination) on yield decline on different soil types, slopes, and soil depths are presented in Figure 5.2.

## The Impacts of Drought

The effects of *belg* season drought on household welfare, income per capita, crop sale, risk premium, on-farm labor, and credit demand are presented in Table 5.3 for the two-oxen household group. This group farms 70 percent of the land area and is therefore the dominant land user group. We therefore chose to focus the modeling on this group.

The effect of providing credit for fertilizer (unconstrained) is compared to the case when credit access is constrained. The models have been run for 10 and 20 percent risk of drought. We see that households with unconstrained access to credit to some extent compensate for the increasing risk of drought by reallocating their production such that crop sales are lower in good years (no drought) to reduce the need to buy crops (food) in case of drought. With constrained access to credit they are less able to do this and they even become net buyers of crops in good years after a few years owing to land degradation and population growth. Provision of credit and fertilizer supply may therefore to some extent reduce the need for food aid in drought years. Credit and fertilizer use helps also to better sustain household welfare while the

**Table 5.1 Barley yields with and without conservation on regosols without fertilizer or manure application**

| Year | Conservation technology | Soil depth <30 cm | Soil depth 30–50 cm | Soil depth >50 cm | Steep slope soil depth <30 cm |
|---|---|---|---|---|---|
| 1 | No | 300.9 | 755.8 | 888.2 | 289.1 |
| | Yes | 306.5 | 759.1 | 888.8 | 299.0 |
| | Yes[a] | 290.8 | 721.1 | 844.3 | 267.7 |
| 2 | No | 289.1 | 749.4 | 887.0 | 265.3 |
| | Yes | 300.7 | 755.0 | 888.2 | 285.4 |
| | Yes[a] | 284.7 | 718.2 | 843.8 | 254.0 |
| 3 | No | 277.2 | 742.8 | 885.7 | 240.9 |
| | Yes | 294.8 | 752.9 | 887.7 | 271.6 |
| | Yes[a] | 278.8 | 715.2 | 843.2 | 241.6 |
| 4 | No | 265.3 | 736.3 | 884.2 | 216.2 |
| | Yes | 288.6 | 749.7 | 887.1 | 257.5 |
| | Yes[a] | 273.2 | 712.2 | 842.7 | 229.0 |
| 5 | No | 253.2 | 730.0 | 882.7 | 190.9 |
| | Yes | 282.5 | 746.6 | 886.5 | 243.4 |
| | Yes[a] | 267.6 | 709.2 | 842.9 | 216.3 |

[a]If conservation technologies reduce the yields due to their occupation of a part of the area.

development path is clearly Malthusian with constrained access to credit for fertilizer (Table 5.3).

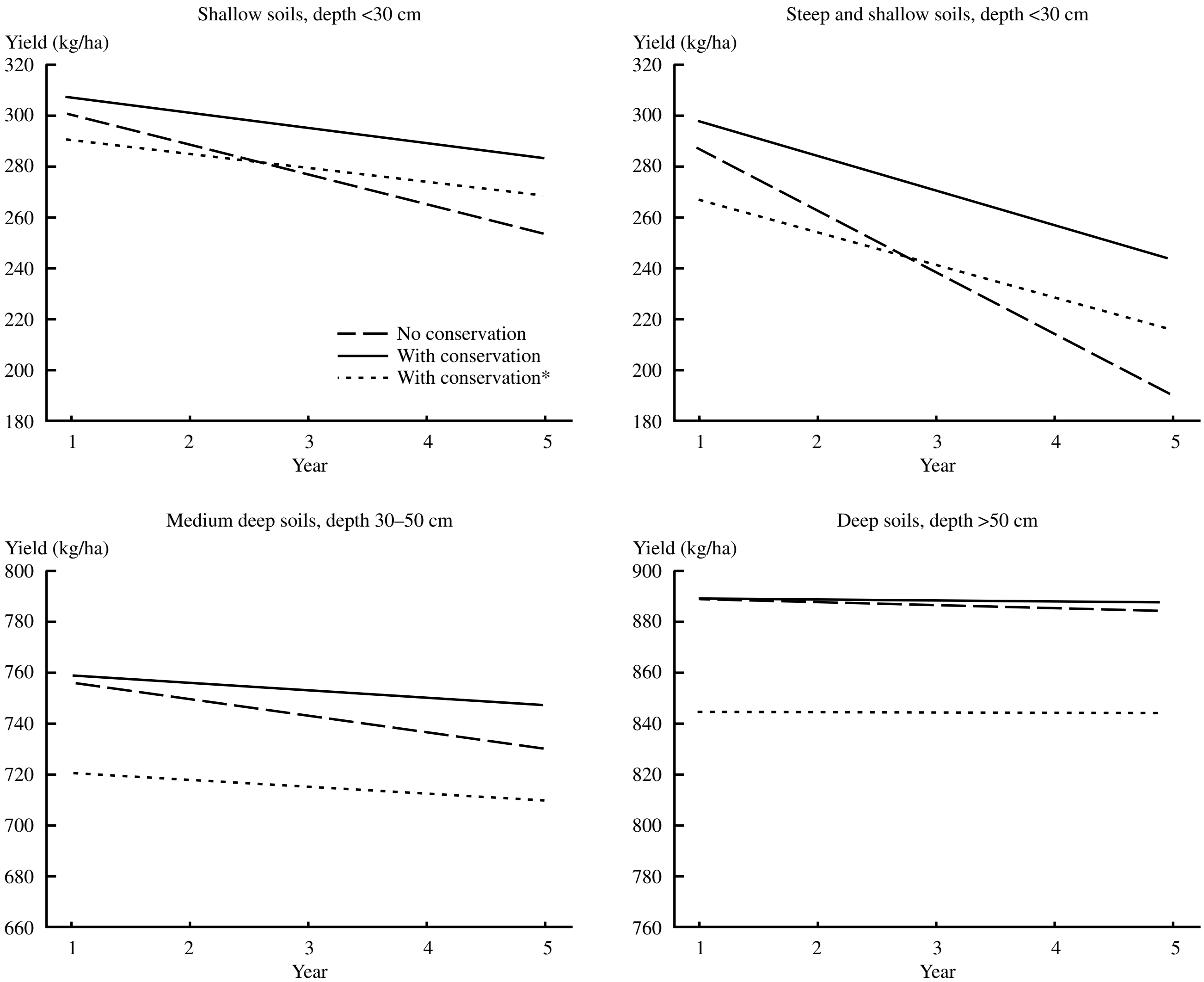
Drought produces both direct and indirect effects. First, there is a direct production effect as crop production is reduced as a result of drought. The *belg* season drought was so severe in 1999 that no crops could be produced in this season. This production loss is therefore equal to the total *belg* season crop production in good years. The fact that the drought strikes over a larger geographical area leads to indirect price effects. Obviously crop prices will increase in drought years and households are typically net buyers of crops in drought years. This implies that they have to buy crops at a higher price. In addition, livestock prices decline when the

**Table 5.2 Barley yield declines (kg/ha) in 5 years for different soil types, with and without conservation technology and with and without fertilizer application**

| Season | Conservation technology | Soil depth <30 cm | | Soil depth 30–50 cm | | Soil depth >50 cm | | Steep slope, soil depth <30 cm | |
|---|---|---|---|---|---|---|---|---|---|
| | | F0[a] | FH[a] | F0 | FH | F0 | FH | F0 | FH |
| *Meher:* | | | | | | | | | |
| Regosols | No | 78.3 | 47.0 | 57.9 | 23.5 | 42.5 | 4.9 | 167.0 | 102.7 |
| | Yes | 38.5 | 22.8 | 27.7 | 10.8 | 18.9 | 1.3 | 91.0 | 54.8 |
| *Belg:* | | | | | | | | | |
| Andosols | No | 89.0 | 60.7 | 67.9 | 38.1 | 51.0 | 20.6 | 182.1 | 126.9 |
| | Yes | 42.4 | 28.6 | 31.9 | 17.4 | 23.6 | 8.8 | 102.2 | 70.0 |

[a]F0 and FH refer to no fertilizer applied and high level of fertilizer applied (= 55 kg of N/ha and 50 kg of $P_2O_5$).

**Figure 5.1 Barley yields on regosols (kg/ha) with different soil depth and slope without fertilizer or manure application**




*If conservation technologies reduce the yields due to their occupation of a part of the area.

drought is severe as people are forced to sell animals instead of crops or to be able to buy more food. This leads to a livestock value loss. We incorporated these losses in the models with and without unconstrained access to credit and with a 10 percent risk of drought. The results are presented in Table 5.4. We see that the production loss is higher with unconstrained access to credit because fertilizer is used on barley in the *belg* season in good years (no drought). The production loss tends to decline over years owing mainly to crop productivity loss. The loss resulting from the need to buy cereals for food in drought years is increasing over time, however, and is not much different with or without unconstrained access to credit for fertilizer. Livestock value losses decline over time as the number of animals declines over time. The total loss is around 80 percent of the poverty line income when credit access is constrained and

**Figure 5.2 Barley yield declines over 5 years on andosols and regosols, without and with fertilizer (55 kg of N/ha and 50 kg of $P_2O_5$), with and without conservation technology**

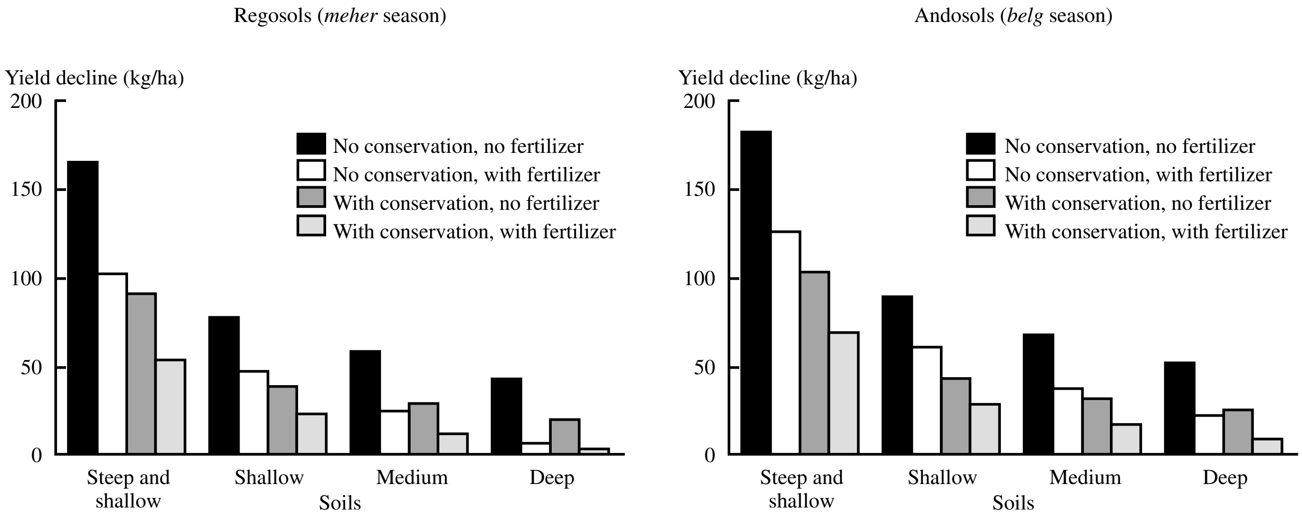



**Table 5.3 Two-oxen household group: Impact of *belg* season drought on household welfare and production, when credit access for fertilizer is unconstrained or constrained**

| Risk of drought | Year | Utility | Expected income per capita (Ethiopian birr) | Net sale crops, no drought | Net sale crops, drought | Drought risk premium | Total on-farm labor | Formal credit demand |
|---|---|---|---|---|---|---|---|---|
| Unconstrained access to credit for fertilizer | | | | | | | | |
| 0.1 | 1 | 0.439 | 562 | 868 | –401 | 0.053 | 440 | 272 |
| | 2 | 0.495 | 571 | 812 | –447 | 0.051 | 430 | 364 |
| | 3 | 0.517 | 582 | 879 | –352 | 0.049 | 449 | 446 |
| | 4 | 0.486 | 564 | 606 | –605 | 0.047 | 451 | 446 |
| | 5 | 0.445 | 536 | 90 | –1,111 | 0.046 | 434 | 384 |
| 0.2 | 1 | 0.265 | 541 | 823 | –350 | 0.090 | 439 | 273 |
| | 2 | 0.328 | 529 | 591 | –339 | 0.068 | 425 | 236 |
| | 3 | 0.352 | 552 | 802 | –270 | 0.079 | 442 | 377 |
| | 4 | 0.323 | 534 | 586 | –465 | 0.074 | 441 | 415 |
| | 5 | 0.298 | 504 | –63 | –960 | 0.062 | 429 | 358 |
| Constrained access to credit for fertilizer | | | | | | | | |
| 0.1 | 1 | 0.323 | 514 | 494 | –337 | 0.035 | 439 | 50 |
| | 2 | 0.355 | 530 | 164 | –623 | 0.031 | 465 | 50 |
| | 3 | 0.206 | 478 | –82 | –873 | 0.031 | 440 | 50 |
| | 4 | 0.274 | 481 | –358 | –1,146 | 0.030 | 405 | 50 |
| | 5 | 0.182 | 446 | –447 | –1,179 | 0.027 | 405 | 50 |
| 0.2 | 1 | 0.220 | 510 | 505 | –324 | 0.064 | 438 | 50 |
| | 2 | 0.245 | 513 | 187 | –600 | 0.057 | 449 | 50 |
| | 3 | 0.155 | 487 | –43 | –831 | 0.056 | 454 | 50 |
| | 4 | 0.172 | 475 | –315 | –1,090 | 0.055 | 396 | 50 |
| | 5 | 0.104 | 440 | –454 | –1,065 | 0.042 | 410 | 50 |

**Table 5.4 Drought year losses and the effects of credit on drought year losses**

| Credit constraint | Year | Production loss[a] (Ethiopian birr) | Purchase food, price loss[b] (Ethiopian birr) | Livestock value loss[c] (Ethiopian birr) | Total loss (Ethiopian birr) | Total loss, as share of poverty line |
|---|---|---|---|---|---|---|
| Yes | 1 | 834 | 214 | 1,013 | 2,139 | 0.79 |
| | 2 | 781 | 415 | 989 | 2,185 | 0.79 |
| | 3 | 792 | 471 | 965 | 2,228 | 0.78 |
| | 4 | 784 | 651 | 932 | 2,367 | 0.81 |
| | 5 | 829 | 689 | 861 | 2,408 | 0.81 |
| No | 1 | 1,321 | 268 | 1,013 | 2,679 | 0.99 |
| | 2 | 1,125 | 313 | 989 | 2,427 | 0.87 |
| | 3 | 1,051 | 412 | 965 | 2,429 | 0.85 |
| | 4 | 1,043 | 552 | 920 | 2,524 | 0.86 |
| | 5 | 1,028 | 632 | 861 | 2,558 | 0.86 |

[a]Production loss is valued at the normal year prices.
[b]In drought year, extra cereals have to be bought at a high price.
[c]Livestock prices are lower in drought year, and this leads to a loss of wealth.

even higher when credit for fertilizer is used. The direct production loss is 30–40 percent of the total loss without access to credit and is 40–50 percent of the total loss with unconstrained access to credit.

## Impact of Credit on Conservation Incentives

The model includes both the options of removal of conservation structures and building of new conservation structures and there is a labor requirement for maintaining conservation structures. Earlier versions of our model were used to test how credit access and fertilizer use affected incentives to conserve land (Shiferaw, Holden, and Aune 2001). In Table 5.5 we present new results on this with the new model in the case when conservation technologies do not reduce initial yields. The table shows that the total erosion (tons of soil per farm) is higher after provision of credit as the area conserved is lower, particularly in the initial years. Conservation increases substantially over the years in both the scenarios; however, the conservation process lags behind in the unconstrained case as compared to the constrained credit access case. Credit access reduces conservation investment by allowing farmers to mask the effects of land degradation in the near term. This may not be a sustainable long-term strategy, however. Some removal of conservation structures occurs in the terminal year.

In Table 5.6 we look at the case when conservation structures reduce initial yields. Here we look at the impact of credit as well as the impact of linking access to credit to a conservation requirement for land where fertilizer is used. We see that erosion rates are higher when initial yields are reduced by conservation structures. More labor is used for removal of conservation structures in the initial year. Provision of credit does not increase erosion as much in the case when conservation structures reduce initial yields because conservation structures are removed also in the credit constrained case. Imposing an interlinkage (cross-compliance) policy that credit for fertilizer only is available for conserved land, reduces erosion levels by 5–15 percent. The reduction is largest in the initial years as fewer conservation structures are removed and more new structures are built. Household welfare is reduced to some extent by the interlinkage policy and total labor requirement is increased in the initial

**Table 5.5 Effects of credit access on conservation investment and soil erosion when conservation technologies do not reduce initial yields**

| Credit constraint | Year | Total erosion, (tons) | Area conserved (ha) | Proportion of all land conserved | Proportion of regosols conserved | Proportion of andosols conserved |
|---|---|---|---|---|---|---|
| Yes | 1 | 100.3 | 1.056 | 0.394 | 0.437 | 0.318 |
| | 2 | 87.6 | 1.504 | 0.561 | 0.713 | 0.298 |
| | 3 | 78.1 | 1.852 | 0.691 | 0.791 | 0.518 |
| | 4 | 71.2 | 1.783 | 0.665 | 0.713 | 0.583 |
| | 5 | 71.9 | 1.713 | 0.639 | 0.672 | 0.583 |
| No | 1 | 109.6 | 0.768 | 0.287 | 0.267 | 0.320 |
| | 2 | 103.2 | 0.845 | 0.315 | 0.325 | 0.298 |
| | 3 | 93.8 | 1.196 | 0.446 | 0.532 | 0.298 |
| | 4 | 76.2 | 1.781 | 0.664 | 0.795 | 0.438 |
| | 5 | 73.0 | 1.667 | 0.622 | 0.647 | 0.580 |

years. Although welfare declines under all the credit scenarios, the decline is much more pronounced when credit is constrained.

An important policy question is how easy or difficult is it to implement this type of interlinkage policy. There are extension agents staying in Andit Tid and they are already involved in promoting fertilizer use through organizing demonstration plots in farmers' fields. It is therefore relatively easy for them to administer such a cross-compliance requirement. The extension agent in the area told us that he gave credit for fertilizer only for use on flat and good soils. Few households dared to take credit for fertilizer, however, owing to the risk involved. This special credit risk aversion appeared to be due to some bad experiences in the past when the punishment for failing to pay back the credit was quite severe.

**Table 5.6 Effects of credit access and interlinkage requirements of using credit for fertilizer on conserved land only when conservation technologies take 5–10 percent of the land out of production**

| Credit constraint | Interlinked credit to conservation | Year | Utility | Total erosion | Total labor (man-days) | Labor for removal of conservation structures (man-days) | Labor for building of new conservation structures (man-days) |
|---|---|---|---|---|---|---|---|
| Yes | No | 1 | 0.468 | 124.3 | 405 | 19.5 | 0.8 |
| | | 2 | 0.446 | 121.4 | 397 | 0 | 0.1 |
| | | 3 | 0.310 | 113.9 | 417 | 0 | 24.1 |
| | | 4 | 0.189 | 100.2 | 388 | 0 | 29.3 |
| | | 5 | 0.139 | 84.8 | 374 | 0 | 42.3 |
| No | No | 1 | 0.615 | 125.5 | 420 | 19.5 | 0.8 |
| | | 2 | 0.647 | 121.6 | 409 | 0 | 0.1 |
| | | 3 | 0.593 | 115.8 | 420 | 0 | 8.7 |
| | | 4 | 0.533 | 100.9 | 412 | 0 | 43.9 |
| | | 5 | 0.352 | 81.7 | 411 | 0 | 68.9 |
| No | Yes | 1 | 0.575 | 109.2 | 446 | 9.9 | 41.8 |
| | | 2 | 0.631 | 109.2 | 421 | 2.6 | 9.6 |
| | | 3 | 0.580 | 108.8 | 415 | 1.1 | 14.2 |
| | | 4 | 0.529 | 94.8 | 424 | 2.4 | 52.9 |
| | | 5 | 0.299 | 75.7 | 395 | 3.5 | 60.5 |

## Impact of Improved Access to Off-Farm Income

Ten-year models were developed to explore the impact of better access to off-farm income on household welfare, agricultural production, conservation incentives, and soil erosion. The risk of drought in these models was low (10 percent) and so was the level of risk aversion.[29] Higher risk and risk aversion caused infeasibilities when the time horizon was expanded much beyond 5 years. Owing to population increase, land constraints, and land degradation, income per capita would fall by 8 percent over a 5-year period when there is access to credit and by 16 percent when there is no access to credit. We did not manage to make the bioeconomic model solve for a 10-year period when access to both wage employment and credit are restricted at very low levels. The income would be lower than for the case of credit only in Figure 5.3 and decline over time is likely to be more rapid than in the case of credit only. This illustrates the severity of the combined effects of land degradation, increasing population pressure, stagnant technology, and drought risk in the case study area. Households are becoming increasingly dependent on better market access or assistance from the outside in order to avoid starvation.

We see from Figure 5.3 (containing 10 graphs) that unconstrained access to wage employment at the going wage rates in Andit Tid would have substantially improved household income in the area. The fact that households have low levels of off-farm income (Table 5.7) indicates that access to low-wage employment is constrained. This may be due to imperfect information and incentive problems. Otherwise, households in the study area would have worked much more outside the farm given their small farms and the risks of agricultural production. Provision of better employment opportunities for unskilled labor (at low wages) may also substantially improve household income in the study area.

Figure 5.3 shows that unconstrained access to off-farm wage employment substantially improves household cash income and it also stabilizes income over time compared to provision of credit only. We will return to the reason for this later. Unconstrained access to off-farm income reduces the demand for credit for purchase of farm inputs over time. We see from Figure 5.3 that constrained access to off-farm wage employment and land constraints lead to a build-up of unutilized household labor (leisure) owing to limited intensification and extensification opportunities in farming. This is also because the work force grows over time as a result of population growth.

We will now look at how different market access conditions affect the agricultural production over time. Figure 5.3 shows that households without access to off-farm wage employment cultivate more of their land, probably because they have a lower opportunity cost of labor. Unconstrained access to credit but not to off-farm employment creates more incentives for land cultivation than both having access to credit and off-farm employment. Agricultural production is continued on a larger area for a longer period of time when households have access to credit only. The effect on livestock capital of households under the different market access conditions is also illustrated in Figure 5.3. We see that households with access to credit only build up and hold more livestock than households with access to off-farm employment (with or without credit constraint). There is a downward trend in livestock capital over the 10-year period, however, probably as a result of a decline in fodder production.

Households with unconstrained access to credit only remain net sellers of crops in years with good rains for most of the 10-year

[29] They were assumed to be risk neutral.

**Figure 5.3 Impact of improved access to credit, off-farm employment, and both credit and off-farm employment**

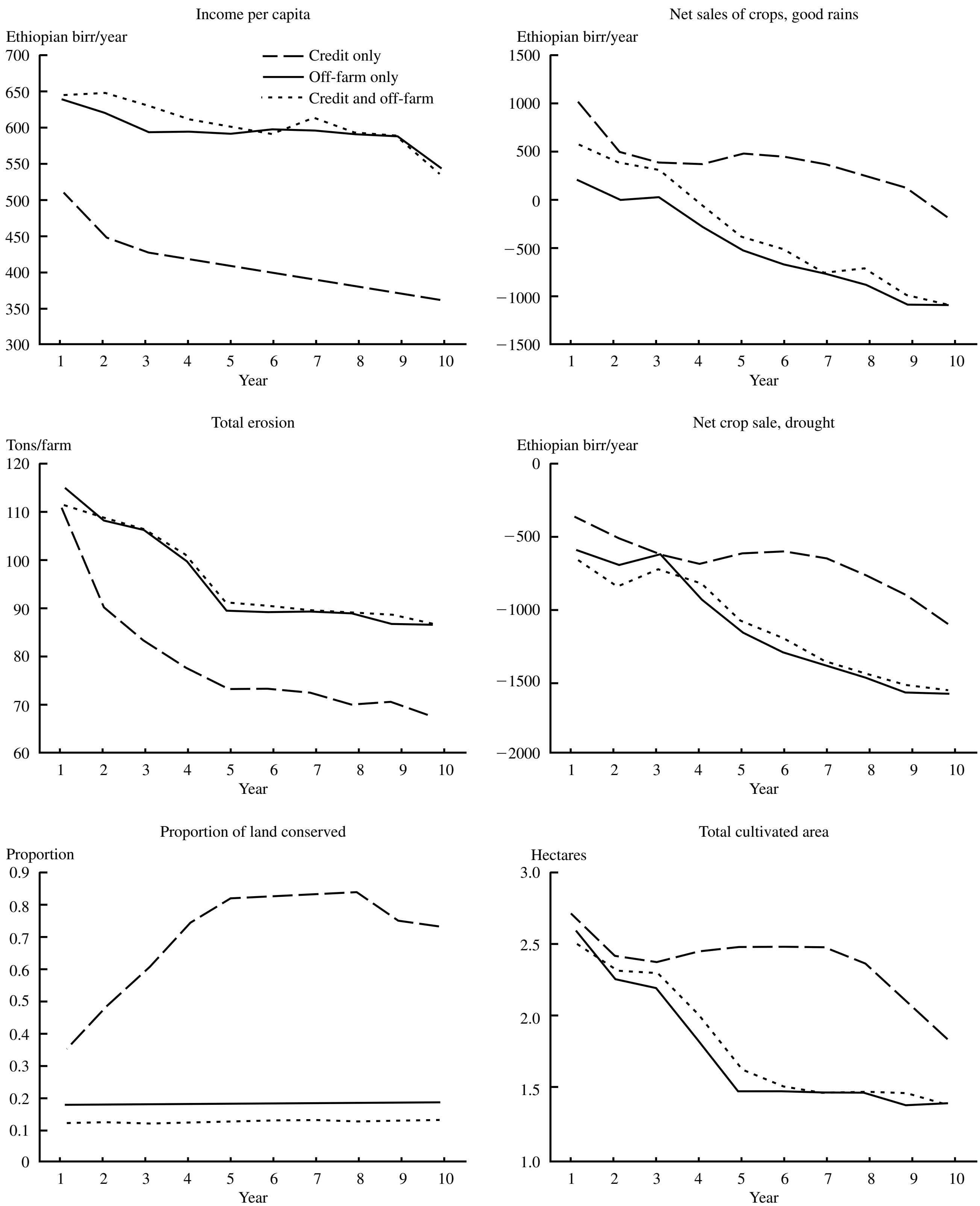


**Figure 5.3—Continued**

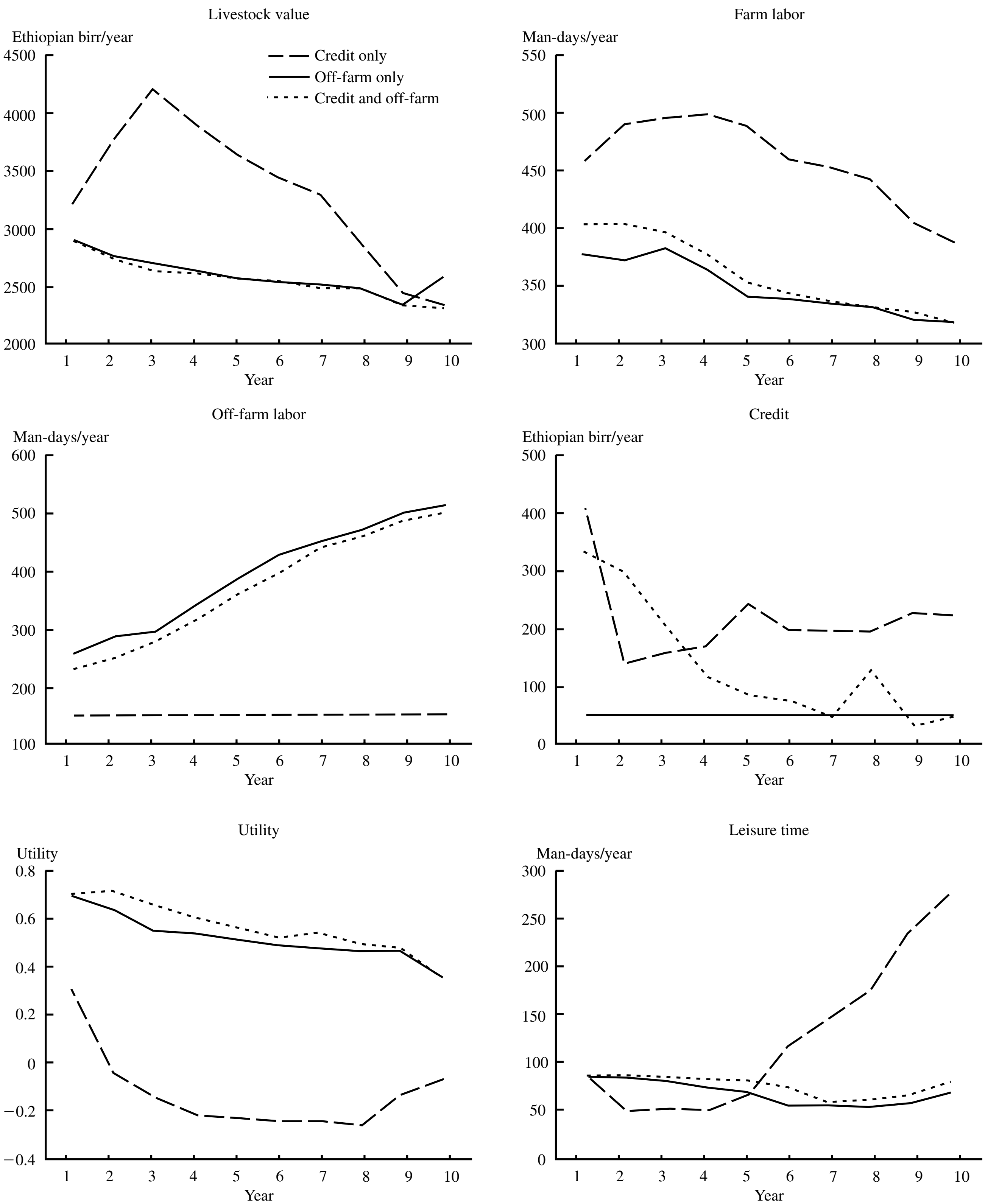


**Table 5.7 Average income by source and household group in Andit Tid, 1999 (Ethiopian birr)**

| Income source | No-oxen households | One-ox households | Two-or-more-oxen households |
|---|---|---|---|
| Wage income | 111 | 63 | 76 |
| Remittance income | 44 | 12 | 48 |
| Common property resource income | 35 | 27 | 37 |
| Business income | 73 | 85 | 38 |
| Food aid | 495 | 517 | 565 |
| Farm income[a] | 394 | 3,301 | 55 |
| Total income | 1,153 | 1,028 | 1,310 |

[a]This is cash income only. It does not include the value of crops or livestock products that were produced and consumed by the household during the year. The year (1999) was a drought year, causing total failure of crop production during the *belg* season.

time period. The surplus declines over time, however, and turns into a net deficit in the last year. Households with access to off-farm income become deficit producers of food crops also in years with good rainfall already after 4 years and the deficit grows to more than 1,000 kilograms of grain per household by the 10th year. Households with unconstrained access to both credit and off-farm wage employment become deficit producers already after 5 years. They produce more food grain in the initial years than households with unconstrained access to off-farm wage employment only but they have a more rapid decline in food grain production and have after 10 years a deficit as large as that of those with unconstrained access to off-farm income only. Better access to off-farm income therefore reduces incentives to produce crops. The pattern is very similar in drought years, but then all households are deficit producers. The deficit increases from about 400 to more than 1,000 kilograms of grains for households with unconstrained access to credit only over the 10-year period, while it increases from 600 to more than 1,500 kilograms for households with access to off-farm wage employment (with or without access to credit).

Households with unconstrained access to credit only put much more labor into farming than households with unconstrained access to off-farm income. Access to credit does not help much for the incentives to work on the farm when there is unconstrained access to off-farm wage employment. The supply of labor for off-farm employment increases steadily owing to the growth in the labor force and the fall in agricultural productivity and thus labor input in agriculture.

Households with unconstrained access to credit only have more incentives to conserve their land and conserve much more of it than households with unconstrained access to off-farm wage employment. Households with unconstrained access both to credit and off-farm wage employment conserve even a smaller share of their land than households with unconstrained access to off-farm wage employment only. Even though households with off-farm employment cultivate small land areas (have less intensive agricultural production), their activity causes more erosion than that of households with access to credit only because they conserve a much smaller proportion of their farmland. It appears therefore that provision of better off-farm employment opportunities does not give win–win benefits as the natural resource base will suffer more because of neglect. We refer to Holden, Shiferaw, and Pender (2004) for further analysis and discussions on the impact of off-farm income on household welfare and sustainability of land use.

## Impact of Introducing FFW Programs

FFW programs have been widely used to target food-insecure people and to promote development in various parts of Ethiopia. FFW was also used to establish conservation structures in Andit Tid in the early 1980s. This was done through a top-down approach that did not involve local people in planning or organization. The farm households themselves therefore had no say with respect to choice of conservation technology or how it fit into the landscape on their farms. This caused many to reject the technologies, as many households were found to have partly or fully removed these technologies on their farms (Shiferaw and Holden 1998). This may also have been due to choice of the wrong type of conservation technology.

We want to assess the impact of new FFW programs in Andit Tid, aiming at providing food security through provision of seasonal employment at a low wage rate (in food). We look at the impact when employment is provided outside agriculture and when employment is provided for conservation investment within agriculture. For the latter case we assume that the investment is taking place on the same households' farms. In both cases the "wage rate" in FFW is 3 kilograms of wheat per day of work, the standard rate mostly used in FFW programs in Ethiopia.

One of the criticisms of FFW is that FFW will undermine incentives to produce own food and to take care of own farms, partly because FFW activities will compete with farming activities of households. Arguments against this are that if FFW is provided outside the main agricultural season such competition may be reduced and FFW will largely be additional. In Andit Tid there are two growing seasons. It is most relevant to provide FFW after the short rains, that is, in the period March to May. However, FFW may compete with households' own conservation activities in this period, as these typically are carried out in the slack season.

In our first simulation we look at impact of provision of FFW when FFW is not used for conservation, when households have constrained access to the labor market, and land conservation technologies do not reduce initial yields. We see from Figure 5.4 that FFW increases income per capita compared to the model without access to FFW. We also see that own food production is reduced in normal as well as in drought years for households with access to FFW (excluding the food obtained through the FFW activity). We see that farm labor use, including conservation labor use, is reduced for households with access to FFW. This causes a smaller proportion of the farm to be conserved and total soil erosion to be larger for households with access to FFW. Total leisure time is reduced for households with access to FFW, indicating that FFW has substituted not only for farm labor but also for leisure time. There are therefore clear costs of providing FFW for poverty reduction and food security provision in this case, as it reduces incentives for own food production and conservation and increases the dependency on assistance from outside.

In our second simulation we look at the impact of FFW when FFW is used for conservation on the same households' farms, when they have constrained access to the labor market, and conservation does not reduce initial yields. The results are presented in Figure 5.5. We see from Figure 5.5 that household income per capita is increased for households with access to FFW. We also see that FFW stimulates land conservation and this leads to less soil erosion. The impact on household food production is small.

In the third simulation we have altered two of the initial assumptions and look at the impact of FFW when FFW is used for conservation, when households have unconstrained access to the labor market (better non-farm employment opportunities), and conservation technologies reduce initial yields (lower incentives to conserve land). The results of the model simulations are

**Figure 5.4 Impact of introducing food-for-work (FFW) when FFW is not used for conservation, access to the labor market is constrained, and land conservation does not reduce initial yields**

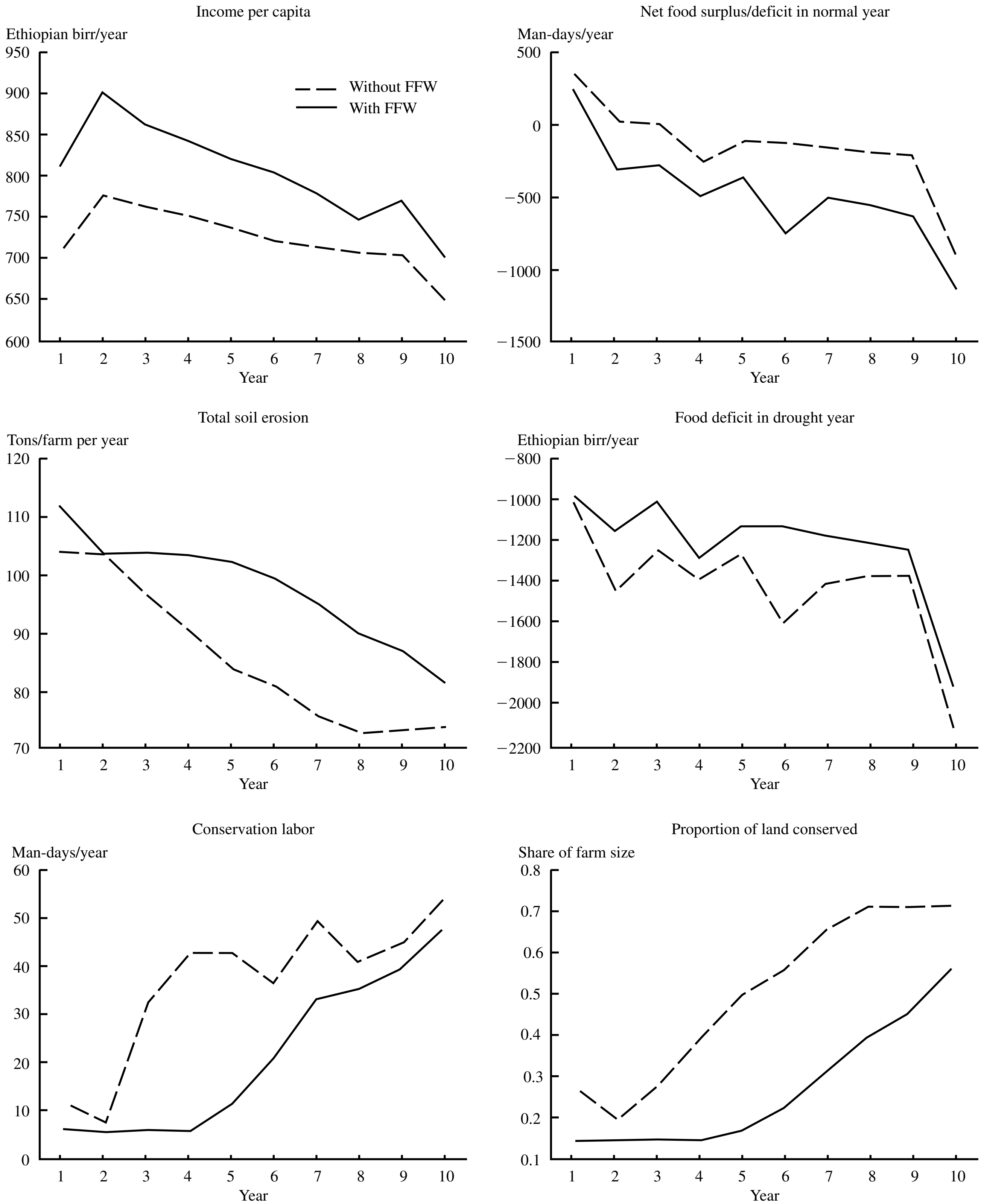
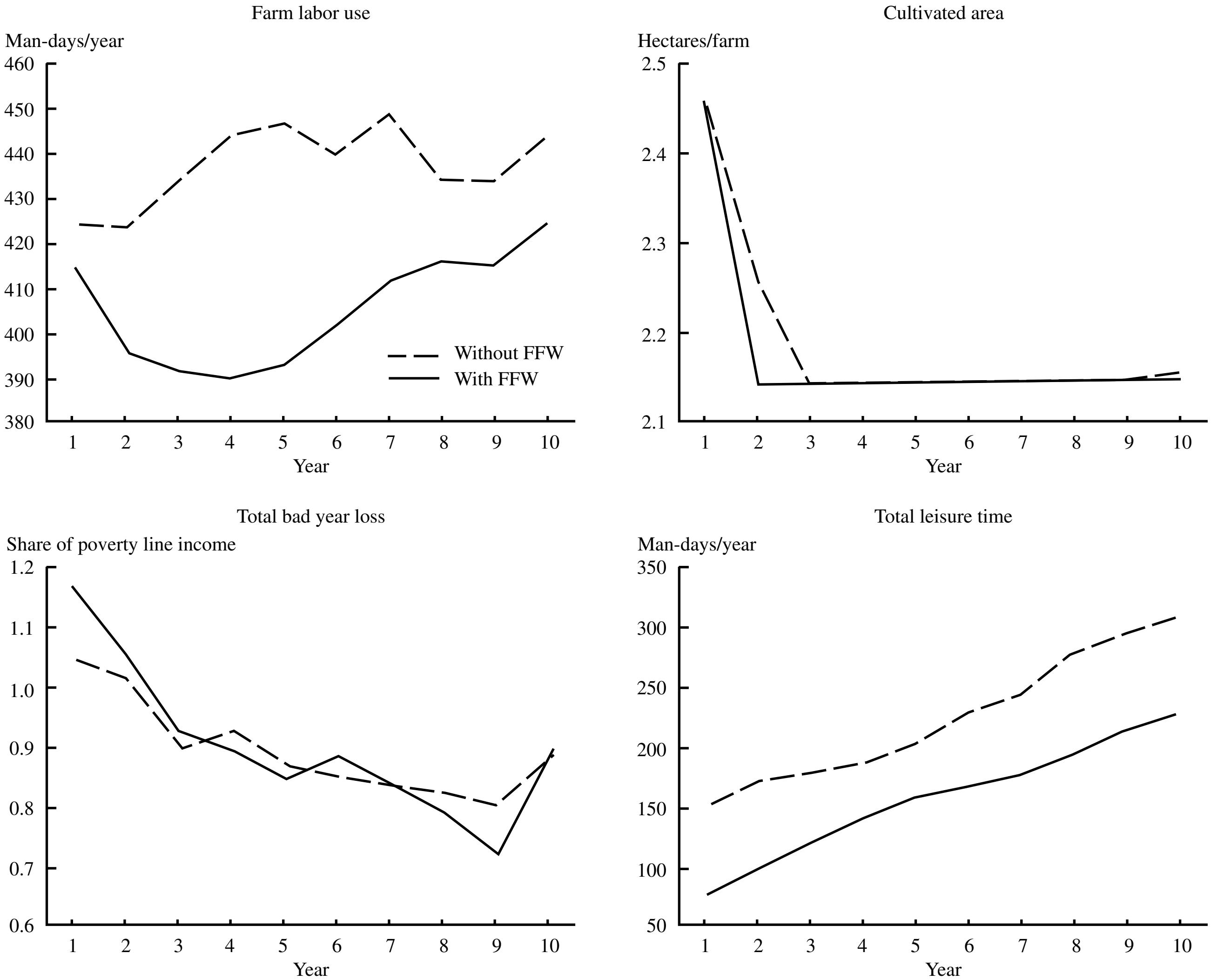


**Figure 5.4—Continued**




included in Figure 5.6 Household income per capita is increased for households with access to FFW also in this case but less so than when access to the labor market was constrained. This implies that the payment from FFW is higher than in the labor market. We also see that FFW substitutes for other off-farm work in this case.[30] On the other hand, FFW stimulates own food production and reduces food deficits in normal as well as drought years, and particularly so toward the end of the 10-year period for which the models have been run. This is largely because FFW is used for land conservation, which makes farm production more sustainable. Without FFW, households do not invest in conservation in this case because conservation reduces initial yields and because they have alternative off-farm employment opportunities.

We see that the effects of FFW on food production and conservation of land can be

[30]FFW is available only seasonally and crowds out other off-farm work in this period. Households engage in other off-farm work in other seasons when they do not have access to FFW.

**Figure 5.5 Impact of food-for-work (FFW) when FFW is used for land conservation, access to the labor market is constrained, and land conservation does not reduce initial yields**

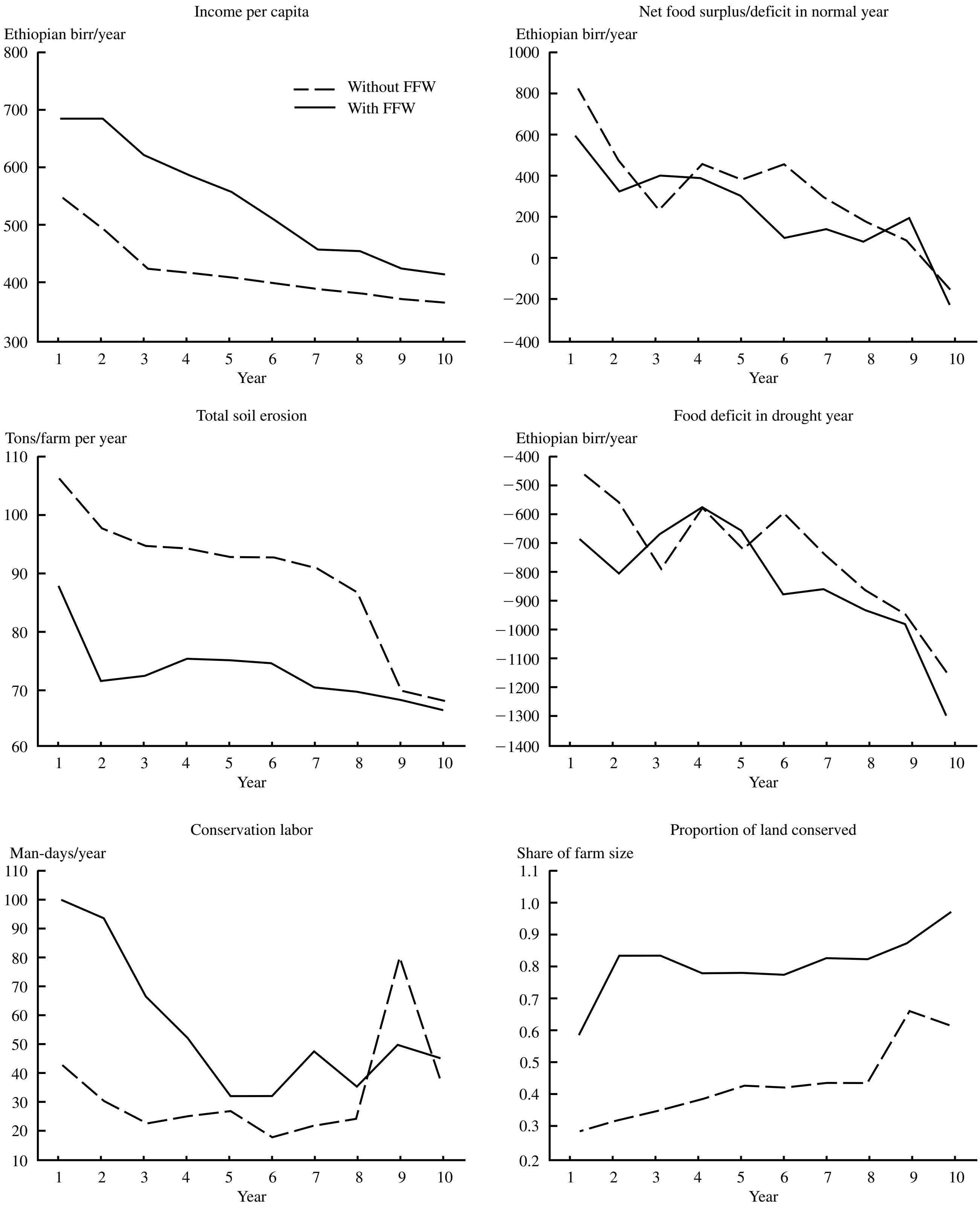
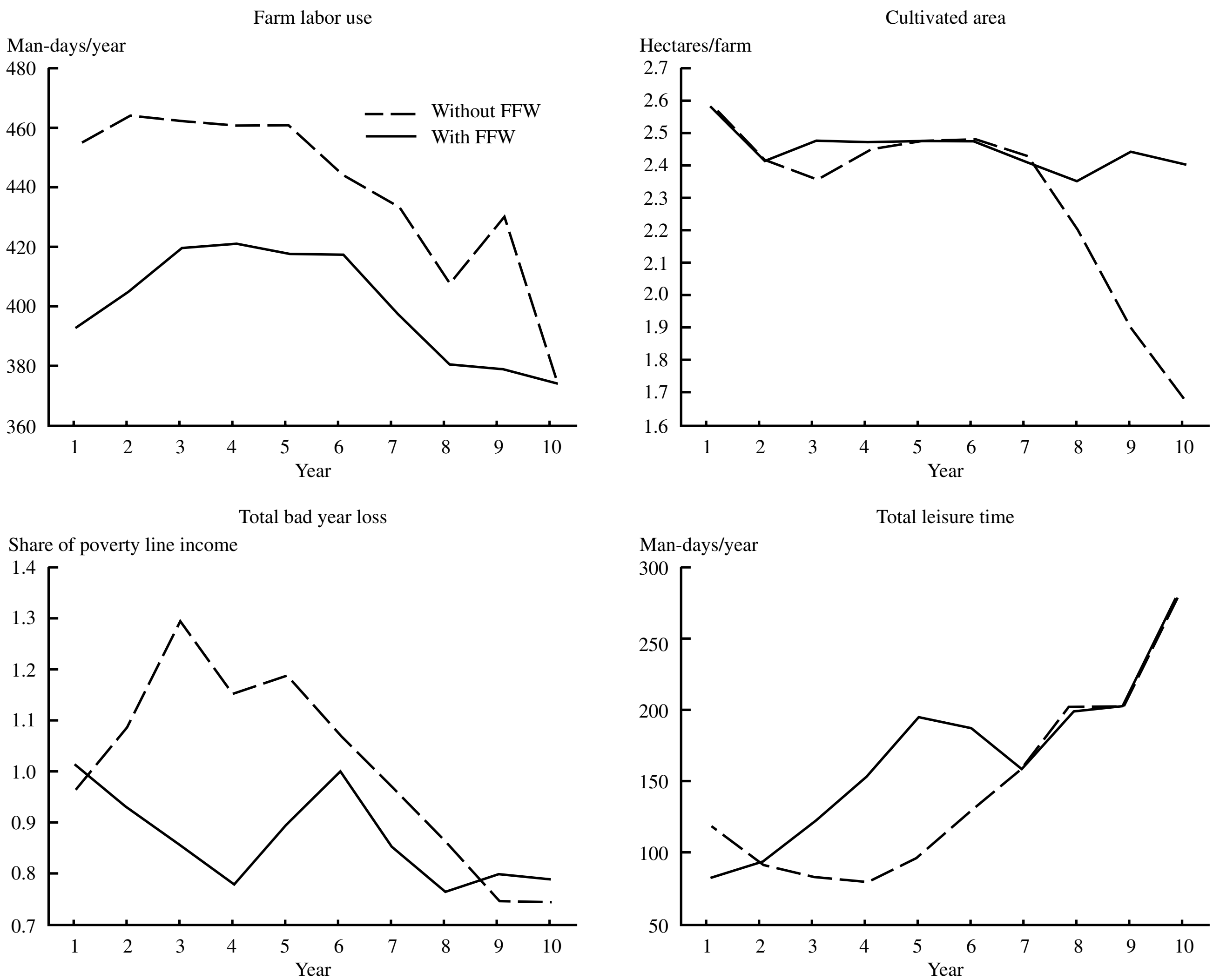


**Figure 5.5—Continued**




very different depending on how and for what activities FFW is used, on the characteristics of the labor market, and on the impact of conservation technologies on short-term yields. We also see that the FFW "wage rate" of 3 kilograms of wheat may be too high and that better poverty targeting may be achieved by lowering the rate to 2 or 2.5 kilograms of wheat per day of work. The food would then probably reach more needy (more efficient self-selection) and a larger number of households. FFW may reduce incentives to conserve land where such incentives exist without intervention when FFW competes with labor used for conservation. On the other hand, FFW may be used to stimulate conservation when there are insufficient incentives to conserve land. This illustrates that care has to be taken when such programs are designed to avoid unwanted disincentive effects and to achieve the objectives of the programs. Good knowledge about the local farming systems, about the local market characteristics and prices, and about the distribution of resources and welfare is needed to avoid design failures. Those who have designed such programs in the past have probably not had such knowledge, and this may also explain the mixed experiences with such programs (Barrett,

**Figure 5.6 Impact of tree planting and food-for-work (FFW) for land conservation**

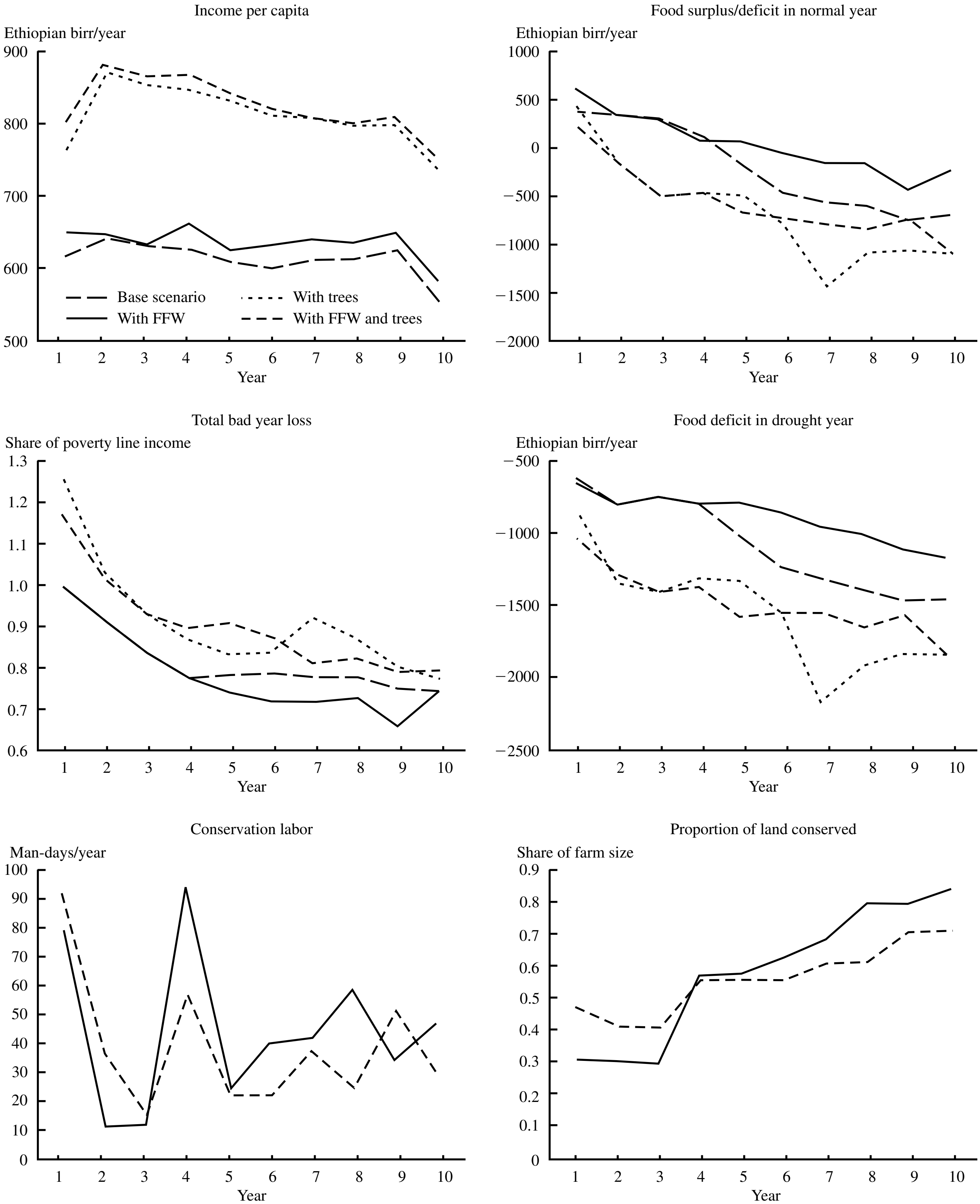
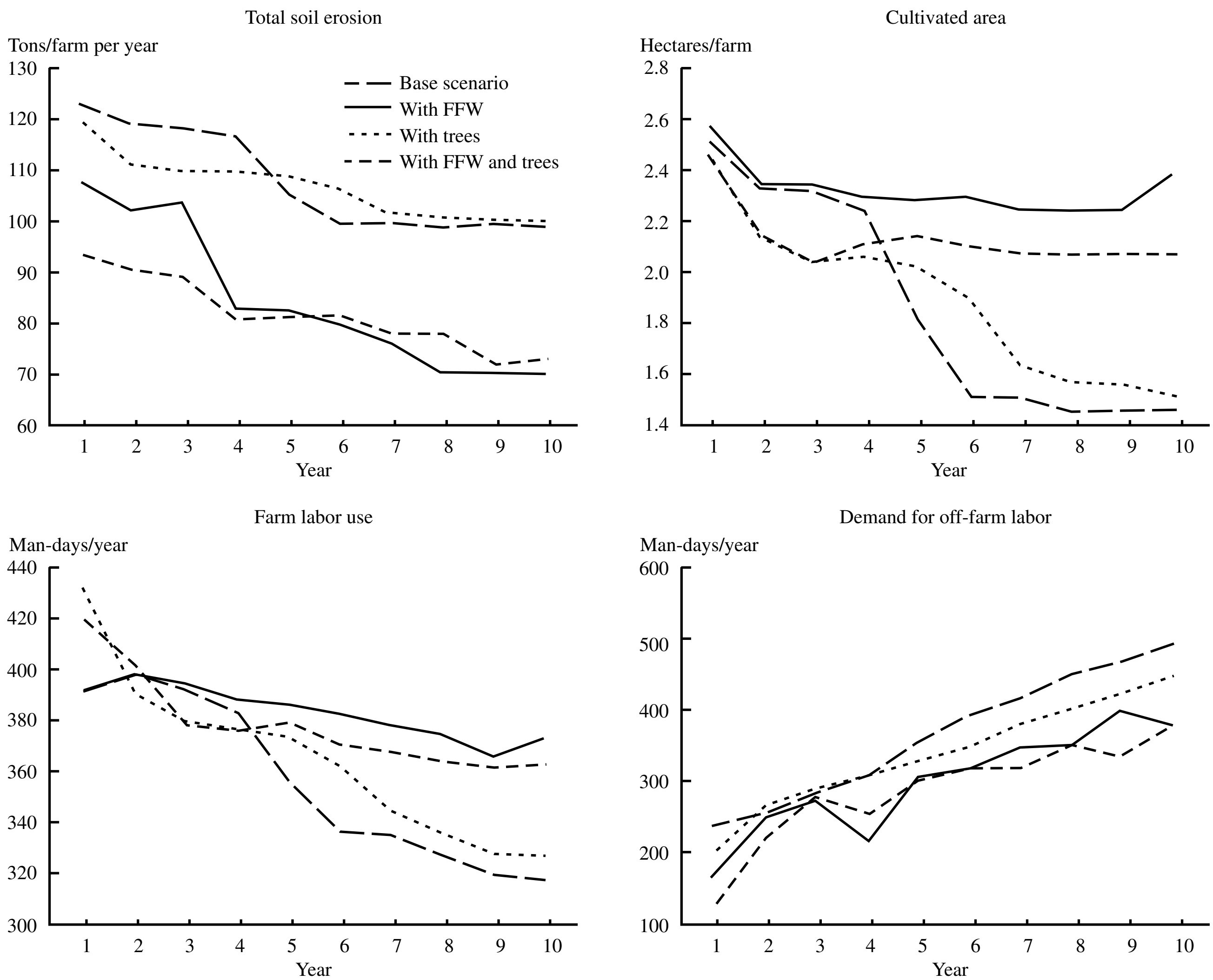


**Figure 5.6—Continued**




Holden, and Clay 2004). We refer to Holden, Barrett, and Hagos (2005) for further analysis and discussions of FFW as an instrument to promote sustainable land management.

## Impact of Stimulating Tree Planting

Planting of trees, especially eucalyptus, may be a promising option for farm households in marginal areas of Ethiopia (Jagger and Pender 2003). In the past, most tree planting took place on government land and community woodlots. However, some tree planting also took place on privately controlled land. Jagger and Pender (2003) suggest that tree planting is most likely to be profitable in areas with low population density, low agricultural potential, good market access, market outlet for tree products, access to long-term credit, and secure access to the benefits from the investments. Holden and Yohannes (2002) found that resource poverty may undermine planting of perennials in southern Ethiopia. If farm households adopt short planning horizons owing to poverty and tenure insecurity, they may not adopt tree planting as it may take 8–15 years before they can harvest the benefits of their investments. It may under such conditions be socially optimal to intervene to stimulate private tree planting as the benefits from intervention may be higher than the costs.

Interventions may take alternative forms depending on local circumstances and various approaches should be tested. Direct regulation is one alternative, as has been recently done in Tigray, where planting of eucalyptus on land suitable for crop production was prohibited in 1997 (Jagger and Pender 2003). Beginning in the late 1990s, the regional government allowed private planting of eucalyptus on community wasteland and steep hillsides. In the Amhara Region distribution of communal lands on long-term lease contracts for private tree planting has also started.

Our case study area has high population density, no access to long-term credit, and farmers may not feel secure that they will be getting the benefits from their tree planting efforts (Holden and Shiferaw 2000). The land redistribution in 1997 may have undermined the feeling of tenure security and reduced the incentives to plant trees. Poverty, credit constraints, and lack of access to tree seedlings may be other reasons for underinvestment in tree planting compared to what would be socially optimal. Our survey showed that farm households in the area are not willing to plant trees on land suitable for crop production but are positive toward tree planting on land unsuitable for cropping. The potential of this option to improve household welfare is therefore what we will explore with our bioeconomic model. We also want to explore the indirect effects on agricultural production and incentives for conservation, considering the income effects and possible competition among alternative uses of family time for agricultural production, conservation, tree production, non-farm employment, and leisure. We do not here explore alternative ways of promoting tree planting but rather assume that the constraints to tree planting have been removed and that a stable tree rotation has been established, given that it is profitable. We therefore try to assess the potential contribution of trees to household income and the impact such production may have on other production and conservation activities.

We allow tree planting only on steep slopes and shallow soils unsuitable for crop production. Almost all land in densely populated Andit Tid has been distributed to individual households. The average area of steep and shallow soils is 0.45 hectares per household. The average area planted with trees on the farms was only 0.09 hectares per household. It should therefore be possible to increase the area planted with trees from 3.3 percent to 18.2 percent of the average farm size without using land that is suitable for crop production.

The high elevation in Andit Tid causes the time from planting to harvesting of eucalyptus to be as long as 12 years. The average price of harvested trees was 12 birr in 1998. This is substantially below the lowest price of 17 birr used by Jagger and Pender in their study in Tigray. This was the case even though Andit Tid is located along the main road between Addis Ababa and the Tigray Region. We also assume away marketing constraints in our analysis and assume that farm households may sell all the trees they produce at the 1998 price. However, we included a small transportation cost for trees of 0.5 birr per tree. We used a planting density of 5,000 trees/hectare and a survival rate of 60 percent. We have not included additional ecological benefits and costs (externalities) of eucalyptus planting in the model as these are highly uncertain and complex and it is not clear whether the net effects are positive or negative (Jagger and Pender 2003).[31] Such effects could be included, however, if they were quantified.

[31]In a recent extension of the model, benefits of carbon sequestration effects of tree planting (and other land-use decisions) have been included by adding a carbon stock to the model (Angelsen et al. 2003).

**Figure 5.7 Impact of planting eucalyptus**

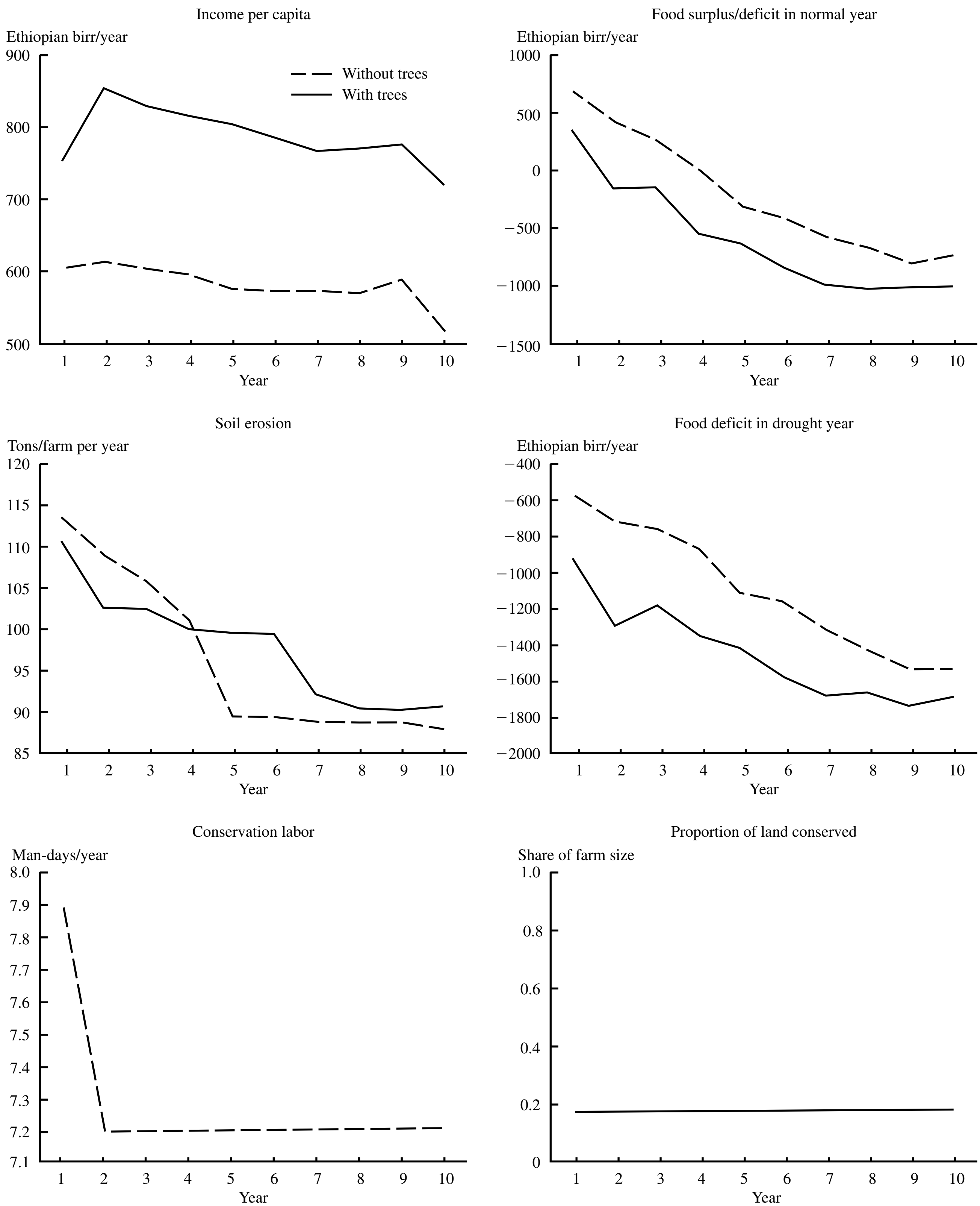


**Figure 5.7—Continued**

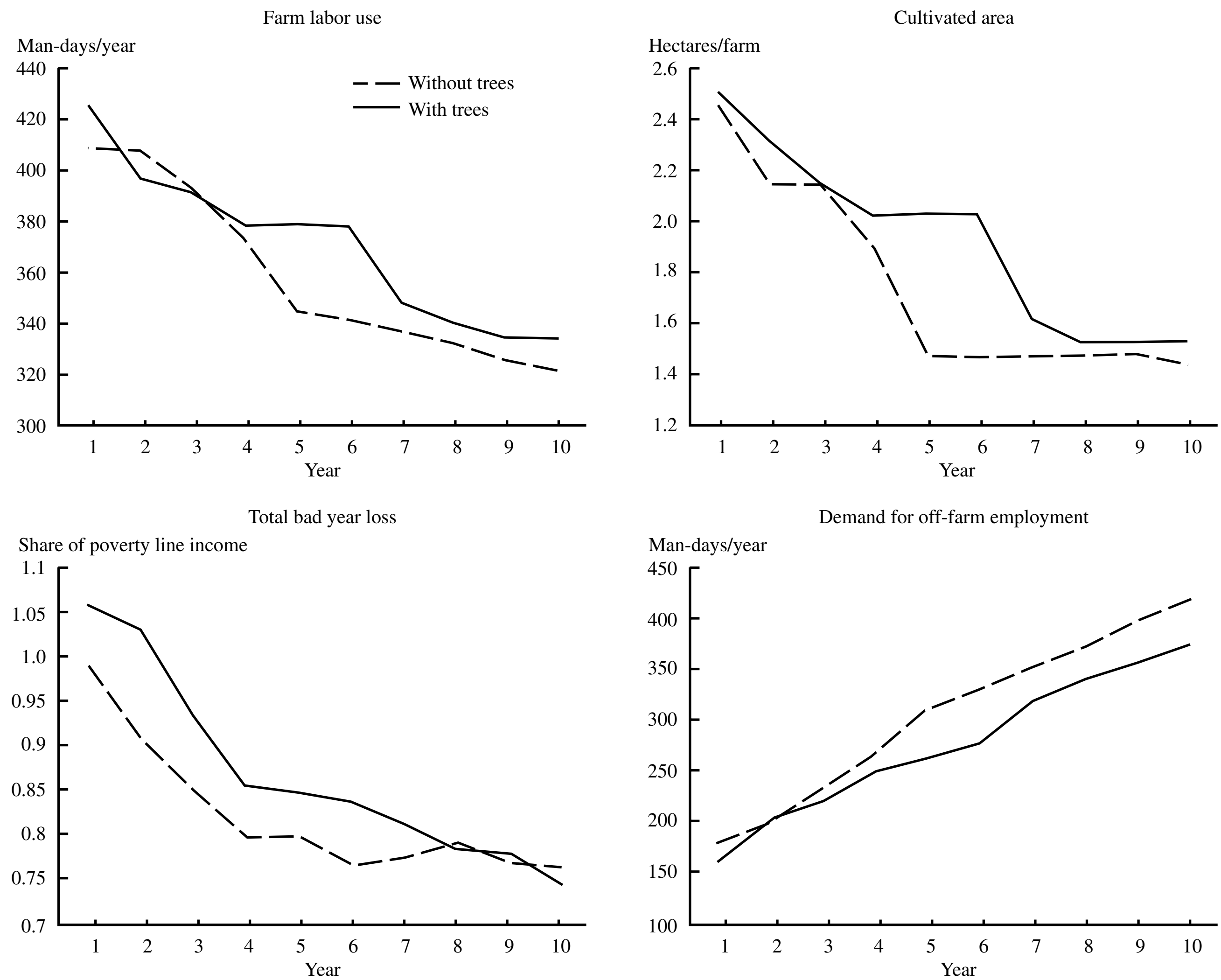



Figure 5.7 illustrates the potential impact of planting of a stable rotation of eucalyptus trees on land unsuitable for crop production in Andit Tid.[32] We have in this case assumed that households have unconstrained access to off-farm employment. We see that planting of eucalyptus on land unsuitable for crop production can increase household income substantially. This is in line with what has been found also in other studies. We see that land for crop production is not used for tree planting and did not reduce incentives to grow food. Larger food deficits are due to higher demand for food as a consequence of the higher income from the sale of trees. Planting of trees had little impact on incentives for conservation of land used for crop production and therefore also had little impact on total soil erosion on farms. Growing of trees reduces the demand for off-farm employment because the return to tree growing is much higher than the wages in the labor market for unskilled labor.

[32]For conservation labor and proportion of land conserved the two scenarios are identical.

It appears that stimulation of planting of eucalyptus may be a promising policy option for degraded drought-prone areas in the Ethiopian highlands provided that market outlets can be identified/developed. Interventions may be necessary to promote this through stimulation of seedling production, mobilization of labor, and identification of suitable areas for planting.

Finally, we looked at the combined effects of FFW employment to promote land conservation and planting of eucalyptus, in the case with unconstrained access to off-farm employment, and when conservation investment reduces initial yields. The results are presented in Figure 5.6.

The impact of FFW on income is small compared to the planting of trees. FFW stimulates land conservation and reduces soil erosion, however, also when tree planting is included. The combination of tree planting and FFW for conservation therefore appears to produce superior outcomes and substantial increases in household income are achieved while conservation of cropped land is also achieved. We have not, however, taken into account the administrative costs of stimulating tree planting and using FFW. That has to be done to make a social cost–benefit analysis of the alternative policies. For further assessment of promotion of tree planting as a strategy to reduce poverty in the Ethiopian highlands we refer to Holden, Shiferaw, and Pender (2004).

## CHAPTER 6

# Conclusions

We have developed bioeconomic models for a severely degraded area with high population density and good market access in the Ethiopian highlands. The area has recently been severely affected by droughts in the *belg* season. We have developed models to assess the impacts of the drought on household production and welfare. We use the models to assess both the direct production losses and the indirect losses due to price changes for crops and livestock. Households will need to buy cereals at a high price in drought years to meet their food needs and/or depend on food aid. Land degradation and population growth have increased the need to purchase food over time and the area has changed from being a surplus producer to a net buyer of cereals. Furthermore, severe drought causes livestock prices to decline. As livestock is the most important form of household wealth, this indirect effect of the drought is considerable.

We found that provision of credit for fertilizer may increase barley production considerably and make more households surplus producers of grains, at least in years when drought does not occur. As much of the barley is produced in the drought-prone *belg* season, provision of credit for fertilizer does not reduce much the need to purchase cereals in drought years. Higher production in good years may, however, make households more able to cope with the drought year losses. The decline in household welfare over time may also be reduced by provision of credit for fertilizer.

Provision of credit for fertilizer has a negative effect on incentives to conserve land and this causes erosion rates to be higher when credit is provided. In the case when conservation structures reduce initial yields it may be useful to interlink provision of credit for fertilizer to a conservation requirement, as this may create additional incentives to conserve land and reduce erosion rates.

Overall, even the combination of conservation structures and high levels of fertilizer use cannot sustain crop yields as erosion cannot be eliminated and soils in the area are shallow. Technical change, off-farm income, population control, or outmigration are necessary to avoid starvation or chronic dependence on food aid.

We find that better access to off-farm income reduces farm households' incentives to invest in conservation and that this leads to more overall soil erosion and more rapid land degradation. This is the case even though total agricultural production (crop and livestock production) and farm input use are reduced when access to off-farm employment is improved. The simulations also indicate that there are entry barriers in wage-employment. Better (unlimited) access to off-farm income at the low seasonal wage rates that are typical in the study area had a considerable positive impact on household welfare but increased the need to import basic food grains to the area. There is therefore a need to complement a policy focusing on the development of the non-farm sector with a policy that ensures conservation of the natural resource base.

We find that food-for-work (FFW) programs may be used to improve household food security and to promote more sustainable land management. There is a danger that such programs may undermine private incentives for food production and land conservation. By linking FFW to conservation investments, negative side effects may be minimized. However, local participation and commitment is important to ensure lasting effects of the investments.

Stimulation of planting of eucalyptus is a promising policy alternative. If land unsuitable for crop production is planted with eucalyptus and market outlets for the trees can be found, this can provide substantial increases in household incomes. This may not have large effects on incentives to conserve cropland.

FFW may be used to stimulate tree planting as well as cropland conservation. Policies combining promotion of tree planting and conservation through FFW may have the potential to achieve win–win benefits in terms of poverty reduction and more sustainable land use. Careful design and implementation is required to maximize such benefits.

## APPENDIX A

# A Dynamic Non-Separable Farm Household Model for Andit Tid, Ethiopia

Detailed lists of sets, parameters, scalars, variables, and equations in the model are presented in this appendix.

### Sets

| | |
|---|---|
| A | Animal production activities |
| BTYPE | Type of credit |
| C | Crop production activities |
| CA(A) | Animal slaughter activities |
| CC(C) | Consumption activities for crop products |
| CR(C) | Consumption of cereals |
| CTCH(TECHL) | Conservation technology |
| E(A) | Existing seed animals |
| FERT | Type of fertilizer |
| FERTL | Levels of fertilizer |
| LAND | Land-use category |
| NCTCH(TECHL) | Traditional technology |
| NP | Soil nutrients nitrogen and phosphorus |
| NUT | Nutrients for human consumption |
| PA(A) | Animal purchase activities |
| PAP | Purchased consumption commodities of animal origin |
| PL(C) | Consumption of pulses |
| PULSE(C) | Pulse crops |
| R(A) | Livestock rearing activities |
| RAMBK(A) | Rams and bucks |
| S | Season for labor use |
| SA(A) | Animal sale activities |
| SC(C) | Sale activities for crop products |
| SD(S) | Dry seasons |
| SHG(A) | Shoats |
| T | Time periods |
| TECHL | Land management type |
| TFIRST(T) | First period |
| TLAST(T) | Last period |

## Parameters

| | |
|---|---|
| TABLE ANPRICE(PAP,*) | Prices of purchased animal products |
| TABLE CALNUT(NUT,*) | Calorie composition of nutrients (kcal/kg) |
| TABLE CLOCUP(C,LAND,TECHL,FERTL,S) | Months of land occupation by crops (ha) |
| TABLE CONSERL(LAND,*) | Labor demand for conservation and other land-specific parameters |
| TABLE CPRICES(C,*) | Prices of purchased crops and nutrient composition |
| TABLE CREDINT(BTYPE,*) | Interest rate on credit |
| TABLE CRESNPC(C,NP) | Nutrient composition of crop residues (kg/ton) |
| TABLE CROPNPC(C,*) | Nutrient composition of grains (kg/ton harvested) |
| TABLE CROPYL(LAND,TECHL,C) | Crop yields (kg/ha) without fertilizer |
| TABLE DRYMREQ(A,*) | Livestock dry matter requirements (tons/year) |
| TABLE EGGNCOM(*,*) | Nutrient composition of farm-produced eggs |
| TABLE FERESPN(C,LAND,*) | Marginal responses to nitrogen fertilizer for crops (kg/ha) |
| TABLE FERESPP(C,LAND,*) | Marginal responses to phosphorus fertilizer for crops (kg/ha) |
| TABLE FERPRICE(FERT,*) | Prices of fertilizer inputs |
| TABLE FERTNUT(FERT,NP) | Fertilizer nutrients in proportion |
| TABLE FERTZ(NP,FERTL) | Fertilizer use levels for crops (kg/ha) |
| TABLE HBLABS(S,*) | Human labor supply in each season in days |
| TABLE LABORUSE(C,LAND,TECHL,FERTL,S) | Human labor use on crops |
| TABLE LVLABREQ(*,S) | Labor requirements for livestock (herded) |
| TABLE LVPRICE(A,*) | Prices of livestock and nutrient com position |
| TABLE MANNUT(NP,*) | Manure nutrients in proportion |
| TABLE MISC(C,LAND,TECHL,FERTL,*) | Seed used soil loss input cost yield of crops |
| TABLE NDEMPL(NP,*) | Nitrogen demand for pulses |
| TABLE NUTCRQC(C,*) | Household nutrient requirements from cereals |
| TABLE NUTPRQM(*,*) | Household nutrient requirements from meat |
| TABLE NUTPRQP(C,*) | Household nutrient requirements from pulses |
| TABLE OXENLABU(C,LAND,TECHL,FERTL,S) | Oxen labor use on crops |
| TABLE PERCONC(NUT,*) | Calorie consumption from nutrients (percent) |
| TABLE PLANTLAB(S,*) | Labor requirements (workdays/ha) for planting trees |

| | |
|---|---|
| TABLE TREEOCUP(LAND,S) | Months of land occupation by eucalyptus trees (ha) |
| TABLE WAGERATE(S,*) | Wage rates |
| TABLE YDEPTH(C,TECHL,LAND,*) | The intercept terms for crops in relation to soil depth |

## Scalars

| | |
|---|---|
| AEMU | Absolute value of elasticity of marginal utility |
| ALFA(T) | Initial cash |
| AREA(LAND) | Available own land in hectares 1999 (ha) |
| CARBRQY(T) | Annual carbohydrate requirements (kg) |
| CONSTPV | Constant term for the *PV* function |
| CRESDP | Crop residue price (per ton) |
| CWRATIO(T) | Consumer worker ratio in period *T* |
| DM | Dry matter content of crop residue |
| FATREQY(T) | Annual fat requirements (kg) |
| GR1DUM | Dummy variable equation (1) for low-income group |
| GRCULU(T) | Growth rate of family size |
| INPUTSHARE | Share of cash farm income used for input purchase next season |
| ISTOCKAV(LAND,NP) | Initial stock of N and P available |
| ISTOCKNP(LAND,NP) | Initial stock of N and P in the soil (tons/ha) |
| KCALPYR | Kilocalories per CU per year |
| LIVN(A) | Number of existing livestock on farm (number) |
| MANPYPA(A) | Collectable dry manure produced (kg) per year per animal |
| MANURL | Labor needed to distribute a ton of manure |
| MUD | Downside risk aversion |
| NCONS | Number of consumers in the family |
| NDEP(T,LAND) | Nitrogen deposition |
| NFAM | Number of family members |
| NUTRQY(T,NUT) | Annual nutrient requirements (kg) |
| NWORK | Number of workers in the family |
| OXHIREP | Price of hiring in oxen pairs per day |
| PDEP(T,LAND) | Phosphorus deposition |
| PEXP(C) | Expected price for crops |
| PEXPA(A) | Expected price for livestock |
| POVLINE(T) | Poverty line in birr per household per year |
| PROTREQY(T) | Annual protein requirements (kg) |
| PROTRQ | Protein requirement per CU in kg/year |
| RISKBELG | Drought risk in *belg* season |
| RISKPROB | Risk probability credit for fertilizer |
| SUBLEIS(T) | Minimum annual leisure consumption and household chores |
| SUBLEISS(T,S) | Minimum seasonal leisure consumption and household chores |
| SUBLEISV(T) | Value of minimum annual leisure consumption and household chores |
| SUBWAGE(T) | Subsistence wage rate |
| TCONS(T) | Total number of consumer units in each period |
| TFLABS(T,S) | Total family labor available in each season |
| TFLABY(T) | Total family labor available in each year |

| | |
|---|---|
| TRCOSTPT(LAND) | Transportation cost per hectare of land harvested |
| TREECOST | Transport cost per unit of trees harvested |
| TREEPR | Price per unit of mature eucalyptus |
| TREEVAL(LAND) | The value of trees harvested per hectare of land |
| TWORK(T) | Total number of workers in each period |

## Variables

### Utility and Income Variables

| | |
|---|---|
| AVGSHVLB(S) | Average shadow value of labor in each season |
| AVGSHVLD(LAND) | Average shadow value of land |
| AVGSHVOX(S) | Average shadow value of oxen labor in each season |
| AVGSHVSE(LAND) | Average shadow value of soil on conserved land |
| AVGSVCAP | Average shadow value of capital |
| AVGSVFED | Average shadow value of animal feed |
| AVGSVNUT(NUT) | Average shadow value of subsistence food |
| AVGSVXCR(C) | Average shadow value of crop production |
| AVGVENCO(LAND) | Average shadow value of soil on non-conserved land |
| BELGRISK(T) | Expected loss due to drought risk in *belg* season |
| BELGRISK(T) | Loss due to increased drought risk in *belg* season |
| BELGRISKN(T) | Normalized risk loss in *belg* season |
| BUYFOOD(T) | Expenditures for buying food in bad year |
| BYLOSS(T) | Total loss in bad year in crop and animal production |
| BYLOSSN(T) | Normalized bad-year loss |
| CASHEXP(T) | Cash expenditure |
| CASHINC(T) | Cash income |
| CEINC(T) | Certainty equivalent income |
| CREDIT(T,BTYPE) | Amount borrowed from formal and informal sources (birr) |
| CRSALLO(T) | Loss of crop sale in bad year |
| DF(T) | Cumulative discount factor in period *T* |
| DF1(T) | Discount factor in period *T* |
| DISCY | Discounted household income (objective function) |
| DOWNRISKV(T) | Downside risk variance in relation to credit |
| DRATE(T) | Discount rate in period *T* |
| GCROPPVB(T) | Gross crop production value *belg* crops |
| GCROPPVM(T) | Gross crop production value *meher* crops |
| GROSCROPB(T,C) | Gross production of *belg* crops |
| GROSCROPM(T,C) | Gross production of *meher* crops |
| HHINCOME(T) | Household full income (with leisure) |
| HHINCOMEN(T) | Normalized household full income and the value of normalized leisure |
| HHINCOMS(T) | Normalized household income (household income divided by poverty line income) |
| HHUTIL(T) | Household utility in period *T* |
| HHUTILB(T) | Household utility if year *T* is bad |
| HHUTILG(T) | Household utility if year *T* is good |
| HHUTILM(T) | Expected household utility in period *T* |
| INTERM(T) | Intermediate product in risk premium calculation |

| | |
|---|---|
| LVSTOCKVE(T) | Livestock expected value in year *T* |
| LVSTSALBY(T) | Livestock sale value in bad year |
| LVSTSALE(T) | Livestock sale value in good year |
| LVSTSALO(T) | Loss in livestock income due to price decline in bad year |
| LVSTVALO(T) | Livestock value loss in bad year |
| LVSTVBY(T) | Livestock value in bad year |
| NCROPPVB(T) | Net crop production value *belg* crops |
| NCROPPVM(T) | Net crop production value *meher* crops |
| NETCASH(T) | Net cash |
| NETCROPB(T,C) | Net production of *belg* crops |
| NETCROPM(T,C) | Net production of *meher* crops |
| NHHY(T) | Household income |
| NHHY2(T) | Household income per consumer unit |
| NHHYBY(T) | Household income in bad year |
| NHHYN(T) | Normalized household income |
| NSALCRBY(T) | Net crop sale value in bad year—negative if net buyer |
| NSALEBCR(T) | Net sale value of *belg* crops |
| NSALECR(T) | Net sale value of all crops |
| NSALEMCR(T) | Net sale value of *meher* crops |
| PV(T) | Present value equivalent in period *T* |
| RISKP(T) | Risk premium on credit |
| RISKP2(T) | Risk premium due to *belg* season drought risk |
| SCALEIS(T) | Normalized household leisure (value of household leisure divided by subleisure) |
| SHAREP(T) | Share rent paid for rented-in land |
| VALCSALE(T) | Total value of crop sales including stored and sold |
| VALIVSAL(T) | Total value of livestock sales |
| VALLANRE(T) | Total income from renting out land |
| VARHHINC(T) | Variance of household normalized income due to *belg* drought risk |
| VLEISURE(T) | The value of leisure |

### Crop Production and Land Management

| | |
|---|---|
| ACULT(T,LAND) | Total area cultivated by land type (ha) |
| AVCAWCON(LAND) | Average area cultivated without conservation |
| BARCONEX(T) | Consumption expenditure on barley |
| CARECON(T,LAND) | Cumulative land area treated with conservation (ha) |
| CARENCON(T,LAND) | Cumulative land area without conservation (ha) |
| CEREALAR(T) | Cereal area (ha) |
| CONSREM(T,LAND) | Conservation area removed in each year (ha) |
| CUMACONS(LAND) | Cumulative area conserved (ha) |
| CUMAREM(T,LAND) | Cumulative conservation area removed up to period *T* (ha) |
| DEPTHCON(T,LAND) | Soil depth (cm) in each period with conservation |
| DEPTHNCO(T,LAND) | Soil depth (cm) in each period without conservation |
| FALCON(T) | Own fallow land conserved |
| FALLOW(T,LAND,TECHL) | Land fallowed (ha) |
| GRAZCON(T) | Own grazing land conserved |
| GRAZEL(T,LAND,TECHL) | Land reserved for grazing purposes (ha) |

| | |
|---|---|
| GROSCRBY(T,C) | Gross crop production in bad year |
| GROSCROP(T,C) | Gross crop production |
| GYIELD(T,C,LAND,TECHL,FERTL) | Net grain yield after erosion |
| HIREIAND(T) | Total area of andosols rented in (ha) |
| HIREIREG(T) | Total area of regosols rented in (ha) |
| HIRINL(T,LAND) | Land rented in by land type (ha) |
| IAREACON(T,LAND) | Land area remaining under conservation from land conserved before year 1 |
| INAREACON(T) | Earlier conserved area remaining conserved |
| INTERCEP(T,C,TECHL,LAND) | The intercept term in the yield soil depth function |
| NAREACON(T) | New area conserved |
| NCONSL(T,LAND) | Total non-conserved land (ha) |
| NETCRBY(T,C) | Net crop production in bad year |
| NETCROP(T,C) | Net crop production |
| OWNCNCON(T,LAND) | Land cropped without conservation each year (only own land) |
| OWNCNCON(T,LAND) | Own land area cropped without conservation in each year |
| OWNUNCON(T) | Own area unconserved (ha) |
| PARECON(T,LAND) | Incremental land area treated in each year (ha) |
| PRCONALL(T) | Proportion of all land conserved |
| PRCONAND(T) | Proportion of andosols conserved |
| PRCONDEE(T) | Proportion of deep soils conserved |
| PRCONLST(T) | Proportion of less steep land conserved |
| PRCONREG(T) | Proportion of regosols conserved |
| PRCONSHA(T) | Proportion of shallow soils conserved |
| PRCONVST(T) | Proportion of very steep land conserved |
| PRODLBY(T,C) | Production loss in bad year |
| PROPCON(T,LAND) | Proportion of total land area conserved (new and old) |
| PROPFGR(T,LAND) | Proportion of total land area fallowed or used for grazing |
| PROPRENT(T,LAND) | Proportion of total land area rented out |
| PULSEA(T) | Total area of pulse crops (ha) |
| RENTEDNC(T,LAND) | Land rented in and cropped without conservation each year (only own land) |
| RENTOUT(T,LAND) | Land rented out |
| RENTUTL(T) | Total area of land rented out (ha) |
| SHARECBY(T,C) | Share crop payment in bad year |
| SHARECR(T,C) | Share crop payment to owner in kilograms of crop |
| TACULT(T) | Total area cultivated (ha) |
| TCROPA(C,T) | Total cropped area of each crop (ha) |
| TLCWCON(LAND) | Sum of area cultivated without conservation |
| TOTACONS(T,LAND) | Total area cultivated with conservation (old plus new conservation) |
| TOTCON(T) | Total own land conserved |
| TREEHARV(T) | Total area of trees harvested (new plus regrowth of trees)(ha) |
| XBUYCON(T,C) | Amount of purchased crop consumption (kg) |

| | |
|---|---|
| XBUYCRBY(T,C) | Extra purchase of crop needed in bad year |
| XBUYSED(T,C) | Amount of crop purchased for seed stock (kg) |
| XCONS(T,C) | On-farm consumption of crop products (kg) |
| XCONSBY(T,C) | Consumption of own produce in bad year |
| XCRESID(T) | Amount of crop residue bought (tons) |
| XCROP(T,C,LAND,FERTL,TECHL) | Crop production activities (ha) |
| XSEED(T,C) | Amount of own crop used as seed stock (kg) |
| XSELCRBY(T,C) | Net sale of crops in bad year |
| XSELCROP(T,C) | Amount of crop production sold (kg) |
| XSTORBY(T,C) | Stored crop in bad year |
| XSTORED(T,C) | Crop stored for next year (kg) |
| XSTOREDC(T,C) | Crop stored in period *T* for consumption the following year (kg) |
| XSTOREDS(T,C) | Crop stored in period *T* for sale the following year (kg) |
| XTCONS(T,C) | Total consumption of food crops (kg) |
| XTCONSBY(T,C) | Total consumption in bad year |
| XTSELL(T,C) | Total annual sale (including stored) of crop products |
| YIELDC(C,LAND,TECHL,FERTL) | Difference in yields first and last year |

### Soil Erosion, Fertilizer Use, Nutrient Depletion

| | |
|---|---|
| ANAPP(T,NP,LAND) | Average N applied (kg/ha) |
| APAPP(T,NP,LAND) | Average P applied (kg/ha) |
| AVEFALL(T,LAND) | Average soil erosion on non-cultivated land (tons/ha) |
| AVENCONL(T,LAND) | Average soil erosion on non-conserved cultivated land (tons/ha) |
| AVGCECON(T,LAND) | Average cumulative soil erosion on conserved cultivated land (tons/ha) |
| AVGCENON(T,LAND) | Average cumulative soil erosion on non-conserved cultivated land (tons/ha) |
| AVGECONL(T,LAND) | Average soil erosion on conserved cultivated land (tons/ha) |
| AVGECONL(T,LAND) | Average soil erosion on own conserved cultivated land (tons/ha) |
| AVGENCON(T,LAND) | Average soil erosion on own non-conserved cultivated land (tons/ha) |
| AVGEOWCL(T,LAND) | Average soil erosion on own cultivated land (tons/ha) |
| AVGSER(T,LAND) | Average soil erosion on cultivated land (tons/ha) |
| AVGSERT(T,LAND) | Average soil erosion on all land by land type (tons/ha) |
| CDEPTHCO(LAND) | Change in soil depth on conserved land |
| CDEPTNCO(LAND) | Change in soil depth on non-conserved land |
| CNPCH(T,TECHL,NP,LAND) | Change in the cumulative available N and P from year to year (kg/ha) |
| CNPSTOCK(T,TECHL,NP,LAND) | Stock of N and P net of erosion and annual losses (tons/ha) |
| CTSOILER(T,LAND) | Cumulative soil eroded up to the period (tons) |
| CUSENCON(T,LAND) | Cumulative soil eroded on non-conserved land up to the period (tons) |

| | |
|---|---|
| CUSERCON(T,LAND) | Cumulative soil eroded on conserved land up to the period (tons) |
| CUSERFAL(T,LAND) | Cumulative soil eroded on fallow and grazing land up to the period (tons) |
| EROSFAL(T,LAND) | Erosion on fallow grazing and plantation land |
| FERTBUY(T,FERT) | Fertilizer bought by type (kg) |
| FERTNP(T,NP,LAND) | N and P applied through fertilizer (kg) |
| NPAVAIL(T,TECHL,NP,LAND) | Change in the available N and P from year to year (kg/ha) |
| NPSTOCKC(T,TECHL,NP,LAND) | Stock of N and P in the soil net of erosion losses (tons/ha) |
| TNPSTOCK(T,NP,LAND) | Level of N and P (kg) for each land type |
| TSERCON(T,LAND) | Amount of soil eroded on conserved land (tons) |
| TSEROS(T) | Total soil erosion |
| TSEROSNC(T,LAND) | Amount of soil eroded on non-conserved land (tons) |
| TSOILER(T,LAND) | Amount of soil eroded in each period (tons) |

### Family and Oxen Time Use

| | |
|---|---|
| CROPLABS(T,S) | Total crop labor by season |
| DRUD1(T,S) | Seasonal extra drudgery linear |
| DRUD2(T,S) | Seasonal extra drudgery quadratic |
| FLABOFM(T,S) | Family labor used in off-farm in each season (man-days) |
| FLABONF(T,S) | Family labor used on-farm in each season (man-days) |
| FLABOXH(T,S) | Family labor used for hiring in oxen in each season (man-days) |
| FLEISURE(T,S) | Family leisure time in each season (man-days) |
| HIREDL(T,S) | Hired labor in each season (man-days) |
| LABCON(T,S) | Labor used for conservation in each season (man-days) |
| LABDEM(T) | Total labor used (family and hired labor) |
| LABFARM(T) | Total labor used in production (man-days) |
| LABHAR(T,S) | Labor used for harvesting trees in each season (man-days) |
| LABMAN(T,S) | Labor used for manure distribution in each season (man-days) |
| LABRCON(T,S) | Labor used for removal of conservation in each season (man-days) |
| LVSTLABS(T,S) | Livestock labor by season |
| ONFLABS(T,S) | On-farm labor by season |
| OXCAPS(T,S) | Seasonal oxen labor capacity |
| OXLABCRS(T,C,S) | Seasonal oxen labor requirement by crop |
| OXLABS(T,S) | Seasonal oxen labor use |
| OXLEIS(T,S) | Seasonal oxen leisure |
| PLANTL(T,S) | Labor used for planting trees in each season (man-days) |
| SVALUELS(T,S) | Shadow value of leisure (birr per man-day) |
| TFLAB(T,S) | Total seasonal family labor use |
| TFLABHOX(T) | Total family labor used for hiring in oxen (man-days) |
| TFLABOFF(T) | Total family labor used off-farm (man-days) |
| TFLABON(T) | Total family labor used on-farm (man-days) |
| THIREDL(T) | Total hired labor time (man-days) |
| TLABCONS(T) | Total labor used in conservation (man-days) |
| TLABHART(T) | Total labor used for harvesting trees (man-days) |
| TLABMAN(T) | Total labor used for distributing manure (man-days) |
| TLABRCON(T) | Total labor used for removal of conservation (man-days) |

| | |
|---|---|
| TLEISURE(T) | Total family leisure time (man-days) |
| TPLANTL(T) | Total labor used for planting trees (man-days) |
| XCROPLABS(T,C,S) | Seasonal labor required by crop |

### Livestock Activities

| | |
|---|---|
| BUYANIP(T,PAP) | Buy animal products (kg) |
| CONSBAN(T,A) | Purchased animal slaughtering activities (heads) |
| CONSOWNA(T,A) | Own animal slaughtering activities (heads) |
| DMANURE(T) | Total manure (kg dry matter) production per year |
| EGGSOWN(T) | Consumption of own eggs |
| LIVBIN(T) | Value 1(0) for livestock production |
| LIVBUY(T,A) | Livestock buying activities (heads) |
| LIVPROD(T,A) | Livestock production activities (heads) |
| LIVREAR(T,A) | Newborn rearing activities (heads) |
| LIVSALE(T,A) | Livestock selling activities (heads) |
| LVSTOCKVAL(T) | Total value of animal stock in each period |
| MANUSE(T) | Amount (kg) of animal manure applied on the fields |
| OXHIREIN(T,S) | Oxen pairs hired in for labor |

### Consumption Requirements

| | |
|---|---|
| FATCAL(T) | Total kilocalories from fat |
| PRCARCAL(T) | Total kilocalories from protein and carbohydrates |
| PROTCAL(T) | Total kilocalories from protein |
| TOTCAL(T) | Total kilocalories |
| TOTCONS(T) | Total kilocalories consumed per consumer unit |

## Equations

### Objective: Discounted Utility

| | |
|---|---|
| OBJEQ | DISCY = SUM(T,HHUTIL(T)*DF(T)) |

### Endogenous Discount Factor and Discount Rates

| | |
|---|---|
| DFEQ(T) | DF1(T) = 1/(1 + DRATE(T)) |
| DFEQ1(T)$(ORD(T) EQ 1) | DF(T)$(ORD(T) EQ 1) = DF1(T)$(ORD(T) EQ 1) |
| DFEQ2(T) | DF(T + 1) = DF(T)*DF1(T + 1) |
| DRATEQ(T) | DRATE(T) = 100/PV(T) – 1 |
| PVEQ(T) | PV(T) = CONSTPV + 0.0046*NHHY2(T) – 6.58*GR1DUM |

### Household Normalized Income plus Leisure in Each Period

| | |
|---|---|
| HINCOMY(T) | NHHY(T) = HHINCOME(T) – VLEISURE(T) |
| NHHYNEQ(T) | NHHYN(T) = NHHY(T)/POVLINE(T) |
| HINCBYEQ(T) | NHHYBY(T) = NHHY(T) – BELGRISK(T)*(1 – RISKBELG)/RISKBELG |
| HINCOMY2(T) | NHHY2(T) = NHHY(T)/TCONS(T) |
| HHNINCEQ(T) | HHINCOMEN(T) = HHINCOME(T)/(POVLINE(T) + SUBLEISV(T)) |
| DOWNRISKEQ(T) | DOWNRISKV(T) = 0.7*RISKPROB*(CREDIT(T,'GC') *(1 + CREDINT('GC','IRATE'))**2) |

| | |
|---|---|
| CREDITRISK(T) | RISKP(T) = 0.5*(AEMU + MUD)*DOWNRISKV(T)/ (NHHY(T)*POVLINE(T)) |
| HHUTILEQ(T) | HHUTIL(T) = (1 – AEMU)/(CEINC(T))**(AEMU – 1) + (AEMU – 1) |
| HHUTILBEQ(T) | HHUTILB(T) = (1 – AEMU)/(HHINCOMEN(T) – RISKP(T) – BELGRISKN(T)*(1 – RISKBELG)/ RISKBELG)**(AEMU – 1) + (AEMU – 1) |
| HHUTILGEQ(T) | HHUTILG(T) = (1 – AEMU)/(HHINCOMEN(T) – RISKP(T) + BELGRISKN(T))**(AEMU – 1) + (AEMU – 1) |
| HHUTILMEQ(T) | HHUTILM(T) = RISKBELG*HHUTILB(T) + (1 – RISKBELG)*HHUTILG(T) |
| BELGRNEQ(T) | BELGRISKN(T) = BELGRISK(T)/HHINCOME(T) |
| VARHHINCEQ(T) | VARHHINC(T) = (BELGRISK(T))**2*(1 – RISKBELG) + BELGRISK(T)*(1 – RISKBELG))**2 |
| RISKP2EQ(T) | RISKP2(T) = 0.5*AEMU*(VARHHINC(T)**0.5/ HHINCOME(T))**2*HHINCOMEN(T) |
| CEINCEQ(T) | CEINC(T) = HHINCOMEN(T) – RISKP(T) – RISKP2(T) |
| ELEISUR1(T) | VLEISURE(T) = SUM(S,FLEISURE(T,S) *SVALUELS(T,S))SUM(S,SUBLEISS(T,S))*SUBWAGE(T) |
| ELEISUR(T) | SCALEIS(T) = VLEISURE(T)/SUBLEISV(T) |

**Share Rent Payment for Rented in Land**

| | |
|---|---|
| SHAREPMT(T) | SHAREP(T) = SUM((C,LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)$RENT(TECHL) *GYIELD(T,C,LAND,TECHL,FERTL)$RENT(TECHL) *PEXP(C)*CONSERL(LAND,'SHARER')) + SUM((LAND,TECHL),GRAZEL(T,LAND,TECHL) $RENT(TECHL)*CONSERL(LAND,'DMYH') *CONSERL(LAND,'SHARER')*CRESDP) + SUM((LAND,TECHL),FALLOW(T,LAND,TECHL) $RENT(TECHL)*CONSERL(LAND,'DMYH') *CONSERL(LAND,'SHARER')*CRESDP) |

**New Risk in *Belg* Season Crop Production Due to Drought**

| | |
|---|---|
| BELGRISKEQ(T) | BELGRISK(T) = SUM((C,LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)$BELGC(C) *GYIELD(T,C,LAND,TECHL,FERTL)$BELGC(C) *PEXP(C))*RISKBELG |

**Crop Production Value**

| | |
|---|---|
| GCROPPVMEQ(T) | GCROPPVM(T) = SUM(C,NETCROPM(T,C)*PEXP(C)) |
| GCROPPVBEQ(T) | GCROPPVB(T) = SUM(C,NETCROPB(T,C)*PEXP(C)) |
| NCROPPVMEQ(T) | NCROPPVM(T) = GCROPPVM(T) – SUM(C,XBUYSED(T,C)$MEHERC(C)*PEXP(C)) |
| NCROPPVBEQ(T) | NCROPPVB(T) = GCROPPVB(T) – SUM(C,XBUYSED(T,C)$BELGC(C)*PEXP(C)) |
| NSALEMCREQ(T) | NSALEMCR(T) = NCROPPVM(T) – SUM(C,XTCONS(T,C)$MEHERC(C)*PEXP(C)) |

| | |
|---|---|
| NSALEBCREQ(T) | NSALEBCR(T) = NCROPPVB(T)<br>– SUM(C,XTCONS(T,C)$BELGC(C)*PEXP(C)) |
| NSALECREQ(T) | NSALECR(T) = NSALEMCR(T) + NSALEBCR(T) |
| NSALCRBYEQ(T) | NSALCRBY(T) = NSALECR(T) – NCROPPVB(T) |

**Bad Year Losses**

| | |
|---|---|
| CRSALLOEQ(T) | CRSALLO(T) = NSALECR(T) – NSALCRBY(T) |
| BUYFOODEQ(T) | BUYFOOD(T) = – NSALCRBY(T)*0.579 |
| LVSTSALEEQ(T) | LVSTSALE(T) = SUM(A,LIVSALE(T,A)$SA(A)<br>*LVPRICE(A,‘PPRICE’)$SA(A)) |
| LVSALBYEQ(T) | LVSTSALBY(T) = SUM(A,LIVSALE(T,A)$SA(A)<br>*LVPRICE(A,‘PRICEBY’)$SA(A)) |
| LVSTSALOEQ(T) | LVSTSALO(T) = LVSTSALE(T) – LVSTSALBY(T) |
| LVSTVBYEQ(T) | LVSTVBY(T) = SUM(A,LIVPROD(T,A)$E(A)<br>*LVPRICE(A,‘PRICEBY’)$E(A))<br>+ SUM(A,LIVREAR(T,A)$R(A)*LVPRICE(A,‘PRICEBY’)<br>$R(A)) + LIVREAR(T – 1,‘MALEC’)<br>*LVPRICE(‘MALEC’,‘PRICEBY’)<br>+ LIVREAR(T – 1,‘FEMALEC’)*LVPRICE(‘FEMALEC’,<br>‘PRICEBY’) + LIVREAR(T – 2,‘MALEC’)<br>*LVPRICE(‘MALEC’,‘PRICEBY’) + LIVREAR(T – 2,<br>‘FEMALEC’)*LVPRICE(‘FEMALEC’,‘PRICEBY’) |
| LVSTVALOEQ(T) | LVSTVALO(T) = LVSTOCKVAL(T) – LVSTVBY(T) |
| BYLOSSEQ(T) | BYLOSS(T) = CRSALLO(T) + BUYFOOD(T)<br>+ LVSTSALO(T) + LVSTVALO(T) |
| BYLOSSNEQ(T) | BYLOSSN(T) = BYLOSS(T)/POVLINE(T) |

**Household Full Income in Each Period**

| | |
|---|---|
| HFINCOME(T) | HHINCOME(T) = SUM((C,LAND,FERTL,TECHL),<br>XCROP(T,C,LAND,FERTL,TECHL)*GYIELD(T,C,LAND,<br>TECHL,FERTL)*PEXP(C)) – BELGRISK(T) – SHAREP(T)<br>– SUM(C,XBUYSED(T,C)*PEXP(C)) – SUM(FERT,<br>FERTBUY(T,FERT)*FERPRICE(FERT,‘PRICE98’))<br>– XCRESID(T)*CRESDP + SUM(LAND,<br>HARVEST(T,LAND)*TREEVAL(LAND))<br>+ SUM(LAND,RHARVEST(T,LAND)*TREEVAL(LAND))<br>+ SUM(S,FLABOFM(T,S)*WAGERATE(S,‘WHS’))<br>– SUM(S,HIREDL(T,S)*WAGERATE(S,‘WHB’))<br>+ SUM(A,LIVPROD(T,A)$E(A)*DRYMREQ(A,‘CULL’)<br>$E(A)) – SUM(A,LIVREAR(T,A)$R(A)<br>*DRYMREQ(A,‘CULL2’)$R(A)) – SUM(A,LIVBUY(T,A)<br>$R(A)*DRYMREQ(A,‘CULL2’)$R(A))<br>– SUM(A,LIVBUY(T,A)*PEXPA(A))<br>+ SUM(A,LIVSALE(T,A)$SA(A)*PEXPA(A)$SA(A))<br>– SUM(S,OXHIREIN(T,S)*SVALUELS(T,S))*2<br>+ VLEISURE(T) – SUM(BTYPE,CREDIT(T,BTYPE)*<br>CREDINT(BTYPE,‘IRATE’)) |

**Land Constraint**

| | |
|---|---|
| LNCONS(T,S,LAND) | SUM((C,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)*CLOCUP(C,LAND,TECHL,FERTL,S)) + CARTREE(T,LAND) + RENTOUT(T,LAND) + SUM(TECHL,GRAZEL(T,LAND,TECHL)) + SUM(TECHL,FALLOW(T,LAND,TECHL)) ≤ AREA(LAND) + HIRINL(T,LAND) |
| LNCONS2(T,LAND) | CARECON(T,LAND) + IAREACON(T,LAND) + OWNCNCON(T,LAND) + RENTEDNC(T,LAND) + CARTREE(T,LAND) + RENTOUT(T,LAND) + SUM(TECHL,GRAZEL(T,LAND,TECHL)) + SUM(TECHL,FALLOW(T,LAND,TECHL)) = AREA(LAND) + HIRINL(T,LAND) |
| LNCONS3(T,LAND) | HIRINL(T,LAND) = SUM((C,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)$RENT(TECHL)) + SUM(TECHL,GRAZEL(T,LAND,TECHL) $RENT(TECHL)) + SUM(TECHL,FALLOW(T,LAND, TECHL)$RENT(TECHL)) |
| LNCONS4(T,LAND) | RENTEDNC(T,LAND) = SUM((C,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)$RENT(TECHL)) |

**Rental Land Constraint**

| | |
|---|---|
| RENTLNDCON(T,LAND) | HIRINL(T,LAND) ≤ CONSERL(LAND,‘RENTL’) HIRINL.L(T,LAND) = CONSERL(LAND,‘RENTL’) |

**Labor Constraints**

| | |
|---|---|
| SEAXCROP(T,C,S) | XCROPLABS(T,C,S) = SUM((LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL) *LABORUSE(C,LAND,TECHL,FERTL,S)) |
| CROPLABSEQ(T,S) | CROPLABS(T,S) = SUM(C,XCROPLABS(T,C,S)) |
| LVSTLABSEQ(T,S) | LVSTLABS(T,S) = LIVBIN(T)*LVLABREQ(‘COWSD’,S) + LVLABREQ(‘FOD’,S)*LVSTOCKVAL(T)/1700 |
| ONFLABSEQ(T,S) | ONFLABS(T,S) = CROPLABS(T,S) + LVSTLABS(T,S) + LABHAR(T,S) + LABCON(T,S) + LABRCON(T,S) + LABMAN(T,S) |
| SESLBREQ(T,S) | ONFLABS(T,S) = FLABONF(T,S) + HIREDL(T,S) |
| SEALABAL(T,S) | TFLAB(T,S) = FLABONF(T,S) + FLABOFM(T,S) + FLABOXH(T,S) |
| TFLABEQ(T,S) | TFLABS(T,S) = TFLAB(T,S) + FLEISURE(T,S) |

**Shadow Wage Equations/Drudgery Curves**

| | |
|---|---|
| DRUD1EQ(T,S) | DRUD1(T,S) = TFLAB(T,S)/ (TWORK(T)*HBLABS(S,‘LENGTH’)) |
| DRUD2EQ(T,S) | DRUD2(T,S) = (DRUD1(T,S) – 5)**2 |
| SVLEISE(T,S) | SVALUELS(T,S) = 1.5 + 0.08*DRUD1(T,S) + 0.04*DRUD2(T,S) |

### Oxen Power Constraints

| | |
|---|---|
| OXENREQ(T,S) | OXLABS(T,S) ≤ OXCAPS(T,S) + OXHIREIN(T,S) |
| OXLABCRSEQ(T,C,S) | OXLABCRS(T,C,S) = SUM((LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL) *OXENLABU(C,LAND,TECHL,FERTL,S)) |
| OXLABSEQ(T,S) | OXLABS(T,S) = SUM(C,OXLABCRS(T,C,S)) |
| OXCAPSEQ(T,S) | OXCAPS(T,S) = HBLABS(S,'OXENLAB') *LIVPROD(T,'OXENPAIR') + HBLABS(S,'BULLAB')*LIVPROD(T,'BULLS') |
| OXLEISEQ(T,S) | OXLEIS(T,S) = OXCAPS(T,S) – OXLABS(T,S) |
| OXHIREQ(T,S) | OXHIREIN(T,S) = 0.5*FLABOXH(T,S) |

2 days of labor brings a pair of oxen, barter trade only

### Fertilizer

| | |
|---|---|
| FERTUSE(T,NP) | SUM((C,LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)*FERTZ(NP,FERTL)) = SUM(FERT,FERTNUT(FERT,NP)*FERTBUY(T,FERT)) + MANUSE(T)*0.6*MANNUT(NP,'MANCOM') + MANUSE(T – 1)*0.4*MANNUT(NP,'MANCOM') |

### Credit for Fertilizer Constraint

| | |
|---|---|
| FERTCRED(T) | SUM(FERT,FERTBUY(T,FERT) *FERPRICE(FERT,'PRICE98')) ≤ CREDIT(T,'GC') |

### Capital and Credit Constraint

| | |
|---|---|
| CAPITALC(T) | SUM(C,XBUYSED(T,C)*PEXP(C)*(1.05)) + SUM(S,HIREDL(T,S)*WAGERATE(S,'WHB')) + 0.3*CREDIT(T,'GC') ≤ INPUTSHARE *(ALFA(T) + SUM(A,LIVSALE(T – 1,A)$SA(A) *PEXPA(A)$SA(A)) – SUM(A,LIVBUY(T – 1,A) *PEXPA(A) + SUM(C,XSELCROP(T – 1,C)*PEXPA(A)))) |

### Liquidity/Cash Constraint

| | |
|---|---|
| NETCASHEQ1(T) | CASHINC(T) = ALFA(T) + SUM(A,LIVSALE(T,A) $SA(A)*PEXPA(A)$SA(A)) + SUM(C,XSELCROP(T – 1,C)*PEXP(C)) + SUM(C,XSTOREDS(T,C)*PEXP(C)) + SUM(S,FLABOFM(T,S)*WAGERATE(S,'WHS')) |
| NETCASHEQ2(T) | CASHEXP(T) = SUM(C,XBUYSED(T,C)*PEXP(C)*(1.05)) + SUM(FERT,FERTBUY(T,FERT) *FERPRICE(FERT,'PRICE98')) + SUM(C,XBUYCON(T,C)*PEXP(C)*(1.05)) + SUM(A,CONSBAN(T,A)$CA(A)*PEXPA(A) *(1.05)$CA(A)) + SUM(PAP, BUYANIP(T,PAP) *ANPRICE(PAP,'PPRICE')) + XCRESID(T)*CRESDP + SUM(A,LIVBUY(T,A)*PEXPA(A)*(1.05)) + SUM(BTYPE, CREDIT(T – 1,BTYPE) *CREDINT(BTYPE,'IRATE')) |
| NETCASHEQ3(T) | NETCASH(T) = CASHINC(T) – CASHEXP(T) |

**Capital in Last Year**

| | |
|---|---|
| CAPTLAST(T)$TLAST(T) | SUM(A,LIVSALE(T,A)$TLAST(T)$SA(A) *PEXPA(A)$SA(A)) + SUM(C,XSELCROP(T,C)$TLAST(T)*PEXP(C)) + SUM(C,XSTOREDS(T,C)$TLAST(T)*PEXP(C)) ≤ SUM(A,LIVSALE(T – 1,A)$TLAST(T)$SA(A) *PEXPA(A)$SA(A)) + SUM(C,XSELCROP(T – 1,C)$TLAST(T)*PEXP(C)) + SUM(C,XSTOREDS(T – 1,C)$TLAST(T)*PEXP(C)) |
| LVSTSTAB(T) | LVSTOCKVAL(T) ≥ 0.8*LVSTOCKVAL(T – 1) |
| LIVSAL(T)$TLAST(T) | SUM(A,LIVSALE(T,A)$TLAST(T)$SA(A) *PEXPA(A)$SA(A)) ≤ SUM(A,LIVSALE(T – 1,A) $TLAST(T)$SA(A)*PEXPA(A)$SA(A)) |

**Seed Use Constraints**

| | |
|---|---|
| SEEDEQ1(T,C)$TFIRST(T) | XSEED(T,C)$TFIRST(T) = CPRICES(C,'INSEED') |
| SEEDREQ(T,C) | SUM((LAND,FERTL,TECHL),XCROP(T,C,LAND, FERTL,TECHL)*MISC(C,LAND,TECHL,FERTL,'SEED')) = XSEED(T,C) + XBUYSED(T,C) |

**Crop Production Balance**

| | |
|---|---|
| SHARECREQ(T,C) | SHARECR(T,C) = SUM((LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)$RENT(TECHL) *GYIELD(T,C,LAND,TECHL,FERTL)$RENT(TECHL) *CONSERL(LAND,'SHARER')) |
| PRODBAL(T,C) | SUM((LAND,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)*GYIELD(T,C,LAND,TECHL,FERTL)) = SHARECR(T,C) + XCONS(T,C) + XSELCROP(T,C) + XSEED(T + 1,C) + XSTORED(T,C) |
| GROSCROPEQ(T,C) | GROSCROP(T,C) = SUM((LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL) *GYIELD(T,C,LAND,TECHL,FERTL)) |
| GRCROPMEQ(T,C) | GROSCROPM(T,C) = GROSCROP(T,C)$MEHERC(C) |
| GRCROPBEQ(T,C) | GROSCROPB(T,C) = GROSCROP(T,C)$BELGC(C) |
| NETCROPEQ(T,C) | NETCROP(T,C) = GROSCROP(T,C) – SHARECR(T,C) |
| NETCROPMEQ(T,C) | NETCROPM(T,C) = NETCROP(T,C)$MEHERC(C) |
| NETCROPBEQ(T,C) | NETCROPB(T,C) = NETCROP(T,C)$BELGC(C) |
| PRODBAL2(T,C) | XSTORED(T,C) = XSTOREDC(T + 1,C) + XSTOREDS(T + 1,C) |

**Crop Production Balance in Bad Year**

| | |
|---|---|
| PRODLBYEQ(T,C) | PRODLBY(T,C) = SUM((LAND,FERTL,TECHL), XCROP(T,C,LAND,FERTL,TECHL)$BELGC(C) *GYIELD(T,C,LAND,TECHL,FERTL)$BELGC(C)) |
| GROSCRBYEQ(T,C) | GROSCRBY(T,C) = GROSCROP(T,C) – PRODLBY(T,C) |
| SHARECBYEQ(T,C) | SHARECBY(T,C) = SHARECR(T,C) – SHARECR(T,C)$BELGC(C) |
| NETCRBYEQ(T,C) | NETCRBY(T,C) = GROSCRBY(T,C) – SHARECBY(T,C) |
| CRDISPBYEQ(T,C) | NETCRBY(T,C) = XCONSBY(T,C) + XSELCRBY(T,C) + XSEED(T + 1,C) + XSTORBY(T,C) + XBUYCRBY(T,C) |

**Crop Consumption Demand**

```
TCONSEQ(T,C)          XTCONS(T,C) = XCONS(T,C) + XBUYCON(T,C)
                      + XSTOREDC(T,C)
BARCONEXEQ(T)         BARCONEX(T) = XTCONS(T,'BARLEYM')
                      *PEXP('BARLEYM') + XTCONS(T,'BARLEYB')
                      *PEXP('BARLEYB')
BARCONEQ(T)           BARCONEX(T) = 553 + 0.1079*NHHY(T)
                      + 0.000034*NHHY(T)**2
WHECONEQ(T)           XTCONS(T,'WHEAT') = –203.06
                      + 0.1358*NHHY(T) – 0.0000115*NHHY(T)**2
HBCONEQ(T)            XTCONS(T,'HBEAN') = –102.0223 + 0.1342*NHHY(T)
```

**Livestock Feed Requirements**

```
FEEDBAL(T)            SUM((C,LAND,FERTL,TECHL),
                      XCROP(T,C,LAND,FERTL,TECHL)
                      *(GYIELD(T,C,LAND,TECHL,FERTL)/1000)
                      *CROPNPC(C,'SYIELD')) + SUM((LAND,TECHL),
                      GRAZEL(T,LAND,TECHL)*CONSERL(LAND,'DMYH'))
                      + SUM((LAND,TECHL),FALLOW(T,LAND,TECHL)
                      *CONSERL(LAND,'DMYH')) + DM*XCRESID(T)
                      ≥ SUM(A,LIVPROD(T,A)*DRYMREQ(A,'DM'))
                      + SUM((LAND,TECHL),GRAZEL(T,LAND,TECHL)
                      $RENT(TECHL)*CONSERL(LAND,'DMYH')
                      *CONSERL(LAND,'SHARER'))
                      + SUM((LAND,TECHL),FALLOW(T,LAND,TECHL)
                      $RENT(TECHL)*CONSERL(LAND,'DMYH')
                      *CONSERL(LAND,'SHARER'))
```

**Production and Use of Animal Manure**

```
EMANURE(T)            DMANURE(T) = SUM(A,LIVPROD(T,A)*MANPYPA(A))
                      + SUM(A,LIVREAR(T,A)$R(A)*MANPYPA(A)$R(A))
                      + SUM(A,LIVBUY(T,A)$R(A)*MANPYPA(A)$R(A))
                      + LIVREAR(T – 1,'MALEC')*MANPYPA('MALEC')
                      + LIVREAR(T – 1,'FEMALEC')*MANPYPA('FEMALEC')
                      + LIVREAR(T – 2,'MALEC')*MANPYPA('MALEC')
                      + LIVREAR(T – 2,'FEMALEC')*MANPYPA('FEMALEC')
EMANURE2(T)           MANUSE(T) ≤ DMANURE(T)
```

**Fat and Protein Calorie Balance**

*Fat Calories*

```
FATCALE(T)            FATCAL(T) = (SUM(C, XCONS(T,C)*CPRICES(C,'FAT'))
                      + SUM(C,XSTOREDC(T,C)*CPRICES(C,'FAT'))
                      + SUM(C, XBUYCON(T,C)*CPRICES(C,'FAT'))
                      + SUM(A, CONSOWNA(T,A)$CA(A)*LVPRICE(A,'FAT')
                      $CA(A)) + SUM(A, CONSBAN(T,A)$CA(A)
                      *LVPRICE(A,'FAT')$CA(A))
                      + SUM(PAP, BUYANIP(T,PAP)*ANPRICE(PAP,'FAT'))
                      + EGGSOWN(T)*EGGNCOM('FAT','EGGSNU')
                      + LIVPROD(T,'COWS')*LVPRICE('COWS','FAT'))*9
```

*Protein Calories*

| | |
|---|---|
| PROTCALE(T) | PROTCAL(T) = (SUM(C, XCONS(T,C)<br>*CPRICES(C,'PROTEIN')) + SUM(C, XSTOREDC(T,C)<br>*CPRICES(C,'PROTEIN')) + SUM(C, XBUYCON(T,C)<br>*CPRICES(C,'PROTEIN')) + SUM(A, CONSOWNA(T,A)<br>$CA(A)*LVPRICE(A,'PROTEIN')$CA(A))<br>+ SUM(A, CONSBAN(T,A)$CA(A)<br>*LVPRICE(A,'PROTEIN')$CA(A))<br>+ SUM(PAP, BUYANIP(T,PAP)<br>*ANPRICE(PAP,'PROTEIN'))<br>+ EGGSOWN(T)*EGGNCOM('PROTEIN','EGGSNU')<br>+ LIVPROD(T,'COWS')<br>*LVPRICE('COWS','PROTEIN'))*4 |

*Protein and Carbohydrate Calories*

| | |
|---|---|
| PRCARCE(T) | PRCARCAL(T) = (SUM((C,NUT),XCONS(T,C)<br>*CPRICES(C,NUT)$NUTCP(NUT))<br>+ SUM((C,NUT),XSTOREDC(T,C)<br>*CPRICES(C,NUT)$NUTCP(NUT))<br>+ SUM((C,NUT),XBUYCON(T,C)<br>*CPRICES(C,NUT)$NUTCP(NUT))<br>+ SUM((A,NUT),CONSOWNA(T,A)$CA(A)<br>*LVPRICE(A,NUT)$CA(A)$NUTCP(NUT))<br>+ SUM((A,NUT),CONSBAN(T,A)$CA(A)<br>*LVPRICE(A,NUT)$CA(A)$NUTCP(NUT))<br>+ SUM((PAP,NUT),BUYANIP(T,PAP)<br>*ANPRICE(PAP,NUT)$NUTCP(NUT))<br>+ SUM(NUT,EGGSOWN(T)<br>*EGGNCOM(NUT,'EGGSNU')$NUTCP(NUT))<br>+ SUM(NUT,LIVPROD(T,'COWS')<br>*LVPRICE('COWS',NUT)$NUTCP(NUT)))*4 |
| TOTCALE(T) | TOTCAL(T) = PRCARCAL(T) + FATCAL(T) |
| NUTRBALF(T) | FATCAL(T) ≤ 0.3*TOTCAL(T) |
| NUTRBALP(T) | PROTCAL(T) ≤ 0.15*TOTCAL(T) |

| | |
|---|---|
| FATCALE(T) | Total calories from fat |
| PRCARCE(T) | Total calories from protein and carbohydrates |
| TOTCALE(T) | Total calories |

**Household Consumption Requirements**

| | |
|---|---|
| CONSR(T,NUT) | SUM(C,XCONS(T,C)*CPRICES(C,NUT))<br>+ SUM(C,XSTOREDC(T,C)*CPRICES(C,NUT))<br>+ SUM(C,XBUYCON(T,C)*CPRICES(C,NUT))<br>+ SUM(A,CONSOWNA(T,A)$CA(A)<br>*LVPRICE(A,NUT)$CA(A)) + SUM(A,CONSBAN(T,A)<br>$CA(A)*LVPRICE(A,NUT)$CA(A))<br>+ SUM(PAP,BUYANIP(T,PAP)*ANPRICE(PAP,NUT))<br>+ EGGSOWN(T)*EGGNCOM(NUT,'EGGSNU')<br>+ LIVPROD(T,'COWS')*LVPRICE('COWS',NUT)<br>≥ NUTRQY(NUT,T) |

### Consumption of Own Animals

| | |
|---|---|
| OWNACONE(T) | SUM(A,CONSOWNA(T,A)$SHG(A)) + SUM(A,CONSBAN(T,A)$SHG(A)) ≥ 1 |
| SHOATE(TFIRST,A) $RAMBK(A) | CONSOWNA(TFIRST,A)$RAMBK(A) ≤ LIVN(A)$RAMBK(A) – LIVSALE(TFIRST,A)$RAMBK(A) |

### Equations for Livestock Follow Now

| | |
|---|---|
| KEEPLIV(TFIRST,A)$E(A) | LIVPROD(TFIRST,A)$E(A) = LIVN(A) + LIVBUY(TFIRST,A)$E(A) – LIVSALE(TFIRST,A)$SA(A) – CONSOWNA(TFIRST,A)$RAMBK(A) |
| KEEPCOW(T + 1) | LIVPROD(T + 1,‘COWS’) = 0.85*LIVPROD(T,‘COWS’) + LIVBUY(T + 1,‘COWS’) + LIVPROD(T,‘HEIFERS’) |
| KEEPOX(T + 1) | LIVPROD(T + 1,‘OXENPAIR’) = 0.85*LIVPROD(T,‘OXENPAIR’) + LIVBUY(T + 1,‘OXENPAIR’) + 0.5*LIVPROD(T,‘BULLS’) |
| KEEPB(T + 1) | LIVPROD(T + 1,‘BULLS’) = 0.9 *LIVREAR(T – 2,‘MALEC’) + LIVBUY(T + 1,‘BULLS’) – LIVSALE(T + 1,‘BULLS’) |
| KEEPHF(T + 1) | LIVPROD(T + 1,‘HEIFERS’) = 0.9 *LIVREAR(T – 2,‘FEMALEC’) + LIVBUY(T + 1,‘HEIFERS’) – LIVSALE(T + 1,‘HEIFERS’) |

Adjustments based on survey data collected in 1999/2000 in the study site.
Fifteen percent of the cows and oxen are replaced every year.
It may require up to 3 years for calves to become bulls or heifers.
This implies it may require up to 4 years for calves to become cows or oxen.
Ten percent of the calves may have then died before they become bulls or heifers.
The death rates should be deducted for the animals in the nonreproductive ages when they are transferred from period to period.

| | |
|---|---|
| KEEPEW(T + 1) | LIVPROD(T + 1,‘SHEEPEW’) = 0.77 *LIVPROD(T,‘SHEEPEW’) + LIVBUY(T + 1,‘SHEEPEW’) + 0.8*LIVREAR(T – 2,‘LAMBFEM’) |

Twenty-three percent of the ewes and does had to be replaced every year.
It may require up to 3 years for lambs and kids to grow to ewes and does.
Twenty percent of the lambs and kids may have died in the process of rearing.

| | |
|---|---|
| KEEPDOE(T + 1) | LIVPROD(T + 1,‘GOATDOE’) = 0.77 *LIVPROD(T,‘GOATDOE’) + LIVBUY(T + 1,‘GOATDOE’) + 0.8*LIVREAR(T – 2,‘KIDFEM’) |
| KEEPRAM(T + 1) | LIVPROD(T + 1,‘SHEEPRAM’) = 0.95 *LIVPROD(T,‘SHEEPRAM’) + 0.9*LIVBUY(T,‘LAMBMALE’) + 0.8*LIVREAR(T – 1,‘LAMBMALE’) + LIVBUY(T + 1,‘SHEEPRAM’) – CONSOWNA(T + 1,‘SHEEPRAM’) – LIVSALE(T + 1,‘SHEEPRAM’) |

| | |
|---|---|
| KEEPBUK(T + 1) | LIVPROD(T + 1,'GOATBUCK') = 0.95 *LIVPROD(T,'GOATBUCK') + 0.9*LIVBUY(T, 'KIDMALE') + 0.8*LIVREAR(T – 1,'KIDMALE') + LIVBUY(T + 1,'GOATBUCK') – CONSOWNA(T + 1,'GOATBUCK') – LIVSALE(T + 1,'GOATBUCK') |
| KEEPHN(T + 1) | LIVPROD(T + 1,'HEN') = 0.75*LIVPROD(T,'HEN') + LIVBUY(T + 1,'HEN') + LIVREAR(T,'CHICKEN') |

The death rate for rams and bucks is 5 percent, but 20 percent of the male kids and lambs may die in the rearing process (10 percent die in one year).

### Calf Balance

| | |
|---|---|
| MCALFB(T) | LIVREAR(T,'MALEC') + LIVSALE(T,'MALEC') = 0.25*LIVPROD(T,'COWS') |
| FCALFB(T) | LIVREAR(T,'FEMALEC') + LIVSALE(T,'FEMALEC') = 0.25*LIVPROD(T,'COWS') |

The calving rate of a cow is 50 percent (i.e., calves every second year).
This means a cow calves every second year.
The sex ratio of the calves is 50 percent.
Productive life of cows and oxen is 10 years—culling rate is 10 percent.
The mortality rate for cows and oxen is 5 percent.
This means the replacement rate for a cow or oxen is 15 percent per annum.

### Lamb Balance

| | |
|---|---|
| MALLAMB(T) | LIVREAR(T,'LAMBMALE') + CONSOWNA(T, 'LAMBMALE') + LIVSALE(T,'LAMBMALE') = 0.4032*LIVPROD(T,'SHEEPEW') |
| FLAMBB(T) | LIVREAR(T,'LAMBFEM') + CONSOWNA(T,'LAMBFEM') + LIVSALE(T,'LAMBFEM') = 0.4032*LIVPROD(T,'SHEEPEW') |

The lambing rate for sheep is 72 percent (i.e., a ewe lambs one time in 1.39 years)
The litter size is 1.12.
The sex ratio is 50 percent.

### Kid Balance

| | |
|---|---|
| MALKID(T) | LIVREAR(T,'KIDMALE') + CONSOWNA(T,'KIDMALE') + LIVSALE(T,'KIDMALE') = 0.423 *LIVPROD(T, 'GOATDOE') |
| FMLKID(T) | LIVREAR(T,'KIDFEM') + CONSOWNA(T,'KIDFEM') + LIVSALE(T,'KIDFEM') = 0.423 *LIVPROD(T, 'GOATDOE') |

The lambing rate for ewes is 60 percent (i.e., a ewe lambs one time in 1.66 years).
The litter size is 1.41.
The sex ratio is 50 percent.

The life span of a ewe or doe is 8 years (culling rate is 13 percent).
The death rate for a ewe or doe is 10 percent.
Replacement rate is 23 percent.

### Chicken Balance

| | |
|---|---|
| CHICKNB(T) | LIVREAR(T,'CHICKEN') + LIVSALE(T,'CHICKEN') + CONSOWNA(T,'CHICKEN') + EGGSOWN(T) = 15*LIVPROD(T,'HEN') |

### Livestock Wealth

| | |
|---|---|
| LVSTKVAL(T) | LVSTOCKVAL(T) = SUM(A,LIVPROD(T,A)$E(A) *LVPRICE(A,'PPRICE')$E(A)) + SUM(A,LIVREAR(T,A)$R(A) *LVPRICE(A,'PPRICE')$R(A)) + SUM(A,LIVREAR(T – 1,'MALEC') *LVPRICE('MALEC','PPRICE')) + SUM(A,LIVREAR(T – 1,'FEMALEC') *LVPRICE('FEMALEC','PPRICE')) + SUM(A,LIVREAR(T – 2,'MALEC') *LVPRICE('MALEC','PPRICE')) + SUM(A,LIVREAR(T – 2,'FEMALEC') *LVPRICE('FEMALEC','PPRICE')) |
| LVSTVALE(T) | LVSTOCKVE(T) = SUM(A,LIVPROD(T,A)$E(A) *PEXPA(A)$E(A)) + SUM(A,LIVREAR(T,A)$R(A) *PEXPA(A)$R(A)) + SUM(A,LIVREAR(T – 1, 'MALEC')*PEXPA('MALEC')) + SUM(A,LIVREAR(T – 1,'FEMALEC') *PEXPA('FEMALEC')) + SUM(A,LIVREAR(T – 2, 'MALEC')*PEXPA('MALEC')) + SUM(A,LIVREAR(T – 2,'FEMALEC') *PEXPA('FEMALEC')) |

### Total Soil Erosion

| | |
|---|---|
| SEROS(T,LAND) | SUM((C,FERTL,TECHL), XCROP(T,C,LAND,FERTL, TECHL)*MISC(C,LAND,TECHL,FERTL,'SELOSS')) + SUM(TECHL,GRAZEL(T,LAND,TECHL)) *CONSERL(LAND,'EROSFALW') + SUM(TECHL,FALLOW(T,LAND,TECHL)) *CONSERL(LAND,'EROSFALW') + CARTREE(T,LAND)*CONSERL(LAND,'EROSFALW') = TSOILER(T,LAND) |
| TSEROSEQ(T) | TSEROS(T) = SUM(LAND,TSOILER(T,LAND)) |

### Cumulative Soil Erosion

| | |
|---|---|
| CUMSER1(T,LAND) $(ORD(T) EQ 1) | CTSOILER(T,LAND)$(ORD(T) EQ 1) = TSOILER(T,LAND)$(ORD(T) EQ 1) |
| CUMSERT(T,LAND) | CTSOILER(T,LAND) = CTSOILER(T – 1,LAND) + TSOILER(T,LAND) |

### N and P Balance Overtime

| | |
|---|---|
| *TNPE(T,NP,LAND) | TNPSTOCK(T,NP,LAND) = ISTOCKNP(LAND,NP) *(AREA(LAND) + HIRINL(T,LAND)) – CTSOILER(T,LAND)*1000*CONSERL(LAND,NP) |
| *NPSTOK1(T,NP,LAND) | CNPSTOCK(T,NP,LAND) = TNPSTOCK(T,NP,LAND) – 0.01*TNPSTOCK(T,NP,LAND) |

### Investment in Soil Conservation

| | |
|---|---|
| SCONSBAL(T,LAND) | SUM((C,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)$CTCH(TECHL)) + GRAZEL(T,LAND,'CONS') + FALLOW(T,LAND,'CONS') = CARECON(T,LAND) + IAREACON(T,LAND) |
| LABORCON(T) | TLABCONS(T) = SUM(LAND,(CARECON(T,LAND) – CARECON(T – 1,LAND))*CONSERL(LAND, 'CONSLH')) + SUM(LAND,CARECON(T – 1,LAND) *CONSERL(LAND,'MAINTH')) + SUM(LAND, IAREACON(T,LAND)*CONSERL(LAND,'MAINTH')) |
| CONSBAL2(T,LAND) | CARECON(T,LAND) ≥ CARECON(T – 1,LAND) |

### Land Cultivated without Conservation

| | |
|---|---|
| CONSBAL3(T,LAND) | SUM((C,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)$NCTCH(TECHL)) = OWNCNCON(T,LAND) + RENTEDNC(T,LAND) |

### Disinvestment in Soil Conservation

| | |
|---|---|
| REMCONSE(T,LAND) | CONSREM(T,LAND) = CONSERL(LAND,'IAREACON') – CUMAREM(T – 1,LAND) – IAREACON(T,LAND) |
| CUMAREME(T,LAND) $(ORD(T) EQ 1) | CUMAREM(T,LAND)$(ORD(T) EQ 1) = CONSREM(T,LAND)$(ORD(T) EQ 1) |
| CUMAREM2(T,LAND) | CUMAREM(T,LAND) = CUMAREM(T – 1,LAND) + CONSREM(T,LAND) |
| CUMAREM3(T,LAND) | CUMAREM(T,LAND) ≤ CONSERL(LAND,'IAREACON') |

### Soil Erosion on Fallow and Grazing Land

| | |
|---|---|
| ERSFALE(T,LAND) | EROSFAL(T,LAND) = SUM(TECHL,FALLOW(T,LAND, TECHL))*CONSERL(LAND,'EROSFALW') + SUM(TECHL,GRAZEL(T,LAND,TECHL)) *CONSERL(LAND,'EROSFALW') + CARTREE(T,LAND)*CONSERL(LAND,'EROSFALW') |

### Soil Erosion on Conserved Land

| | |
|---|---|
| SERCON(T,LAND) | SUM((C,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)$CTCH(TECHL)*MISC(C,LAND,TECHL,FERTL, 'SELOSS')$CTCH(TECHL)) = TSERCON(T,LAND) |

### Soil Erosion on Non-Conserved Land

| | |
|---|---|
| SERNCON(T,LAND) | SUM((C,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)$NCTCH(TECHL)*MISC(C,LAND,TECHL, |

| | |
|---|---|
| | FERTL,‘SELOSS’)$NCTCH(TECHL)) = TSEROSNC(T,LAND) |

**Average Soil Erosion on Conserved Land**

| | |
|---|---|
| SERCON2(T,LAND) | AVGECONL(T,LAND) = TSERCON(T,LAND)/ (CARECON(T,LAND) + IAREACON(T,LAND)) |

**Average Soil Erosion on Non-Conserved Land**

| | |
|---|---|
| SERCON3(T,LAND) | AVENCONL(T,LAND) = TSEROSNC(T,LAND)/ (OWNCNCON(T,LAND) + RENTEDNC(T,LAND)) |

**Cumulative Average Soil Erosion with Conservation**

| | |
|---|---|
| CUMSECO1(T,LAND) $(ORD(T) EQ 1) | CUSERCON(T,LAND)$(ORD(T) EQ 1) = AVGECONL(T,LAND)$(ORD(T) EQ 1) |
| CUMSECO2(T,LAND) | CUSERCON(T,LAND) = CUSERCON(T – 1,LAND) + AVGECONL(T,LAND) |

**Cumulative Average Soil Erosion without Conservation**

| | |
|---|---|
| CUMSENC1(T,LAND) $(ORD(T) EQ 1) | CUSENCON(T,LAND)$(ORD(T) EQ 1) = AVENCONL(T,LAND)$(ORD(T) EQ 1) |
| CUMSENC2(T,LAND) | CUSENCON(T,LAND) = CUSENCON(T – 1,LAND) + AVENCONL(T,LAND) |

**Cumulative Soil Erosion on Fallow and Grazing Land**

| | |
|---|---|
| CUMSEFAL(T,LAND) $(ORD(T) EQ 1) | CUSERFAL(T,LAND)$(ORD(T) EQ 1) = EROSFAL(T,LAND)$(ORD(T) EQ 1) |
| CUMSFAL2(T,LAND) | CUSERFAL(T,LAND) = CUSERFAL(T – 1,LAND) + EROSFAL(T,LAND) |

**Computation of Change in Soil Depth for the Intercept Term (the yield depth function)**

| | |
|---|---|
| DEPTHCE(T,LAND) | DEPTHCON(T,LAND) = CONSERL(LAND,‘SDEPTH’) – 0.01*CUSERCON(T,LAND) |
| DEPTHNCE(T,LAND) | DEPTHNCO(T,LAND) = CONSERL(LAND,‘SDEPTH’) – 0.01*CUSENCON(T,LAND) |

**Computation of the Yields Intercept Term**

| | |
|---|---|
| INTERCE(T,C,‘CONS’, LAND) | INTERCEP(T,C,‘CONS’,LAND) = CONSERL(LAND, ‘EFARUCON’)*(YDEPTH(C,‘CONS’,LAND,‘INTERCP’) + YDEPTH(C,‘CONS’,LAND,‘LNCOFD’) *DEPTHCON(T,LAND) + YDEPTH(C,‘CONS’,LAND, ‘NLNCOFD’)*DEPTHCON(T,LAND)**2) |
| INTERCEN(T,C,TECHL, LAND)$NCTCH (TECHL) | INTERCEP(T,C,TECHL,LAND)$NCTCH(TECHL) = YDEPTH(C,‘NCONS’,LAND,‘INTERCP’) + YDEPTH(C,TECHL,LAND,‘LNCOFD’) $NCTCH(TECHL)*DEPTHNCO(T,LAND) + YDEPTH(C,TECHL,LAND,‘NLNCOFD’) $NCTCH(TECHL)*DEPTHNCO(T,LAND)**2 |

**Area Cropped with and without Conservation**

| | |
|---|---|
| TOTACONE(T,LAND) | TOTACONS(T,LAND) = CARECON(T,LAND) + IAREACON(T,LAND) + SUM(TECHL, GRAZEL(T,LAND,'CONS')) + SUM(TECHL, FALLOW(T,LAND,'CONS')) |
| TOTCONMAX(T,LAND) | TOTACONS(T,LAND) ≤ AREA(LAND) |

**N and P Balance with and without Conservation Overtime**

| | |
|---|---|
| TNPECON(T,TECHL, NP,LAND) | NPSTOCKC(T,TECHL,NP,LAND) = (ISTOCKNP(LAND,NP) – CUSERCON(T,LAND)*2 *CONSERL(LAND,NP))$CTCH(TECHL) + (ISTOCKNP(LAND,NP) – CUSENCON(T,LAND)*2 *CONSERL(LAND,NP))$NCTCH(TECHL) |

An enrichment factor of 2 is used

| | |
|---|---|
| NPSTOK1(T,'CONS', NP,LAND) | CNPSTOCK(T,'CONS',NP,LAND) = NPSTOCKC(T,'CONS',NP,LAND) – 0.01*NPSTOCKC(T,'CONS',NP,LAND) |
| NPSTOK2(T,TECHL, NP,LAND)$NCTCH (TECHL) | CNPSTOCK(T,TECHL,NP,LAND)$NCTCH(TECHL) = NPSTOCKC(T,TECHL,NP,LAND)$NCTCH(TECHL) – 0.01*NPSTOCKC(T,TECHL,NP,LAND)$NCTCH(TECHL) |
| NPAVALE(T,TECHL, NP,LAND)$(ORD(T) EQ 1) | NPAVAIL(T,TECHL,NP,LAND) = CNPSTOCK(T,TECHL,NP,LAND) – CNPSTOCK(T,TECHL,NP,LAND) |
| NPAVALE2(T,TECHL, NP,LAND)$(ORD(T) GT 1) | NPAVAIL(T,TECHL,NP,LAND) = 0.01*1000*(CNPSTOCK(T,TECHL,NP,LAND) – CNPSTOCK(T – 1,TECHL,NP,LAND)) |

**Cumulative Change in N and P Availability**

| | |
|---|---|
| CNPCHAN(T,TECHL,NP, LAND)$(ORD(T) EQ 1) | CNPCH(T,TECHL,NP,LAND)$(ORD(T) EQ 1) = NPAVAIL(T,TECHL,NP,LAND)$(ORD(T) EQ 1) |
| CNPCHAN2(T,TECHL, NP,LAND) | CNPCH(T,TECHL,NP,LAND) = CNPCH(T – 1,TECHL,NP,LAND) + NPAVAIL(T,TECHL,NP,LAND) |

**Estimation of Crop Yields after Erosion and N Depletion**

| | |
|---|---|
| GYIELDE(T,C,LAND, TECHL,FERTL) | GYIELD(T,C,LAND,TECHL,FERTL) = INTERCEP(T,C,TECHL,LAND) + (FERTZ('NITR', FERTL) + CNPCH(T,TECHL,'NITR',LAND)) *FERESPN(C,LAND,'LNCOF') + (FERTZ('NITR',FERTL) + CNPCH(T,TECHL,'NITR',LAND))*(FERTZ('NITR', FERTL) + CNPCH(T,TECHL,'NITR',LAND)) *FERESPN(C,LAND,'NLNCOF') + FERTZ('PHOS', FERTL)*FERESPP(C,LAND,'LPCOF') + (FERTZ('PHOS',FERTL))*(FERTZ('PHOS',FERTL)) *FERESPN(C,LAND,'NLPCOF') + (FERTZ('NITR',FERTL) + CNPCH(T,TECHL,'NITR',LAND)) *FERTZ('PHOS',FERTL)*FERESPP(C,LAND,'NPCOF') |

### Fertilizer Nutrients N and P Supply

| | |
|---|---|
| FERTUNP(T,NP,LAND) | SUM((C,FERTL,TECHL),XCROP(T,C,LAND,FERTL, TECHL)*FERTZ(NP,FERTL)) = FERTNP(T,NP,LAND) |

### Summing Up on Certain Computed Variables

| | |
|---|---|
| CULTA(T,LAND) | SUM((C,FERTL,TECHL), XCROP(T,C,LAND,FERTL, TECHL)) = ACULT(T,LAND) |
| CULTA2(T) | TACULT(T) = SUM(LAND,ACULT(T,LAND)) |
| CEREALE(T) | SUM((C,FERTL,TECHL,LAND)$CR(C), XCROP(T,C, LAND,FERTL,TECHL)) = CEREALAR(T) |
| PULSEAR(T) | SUM((C,FERTL,TECHL,LAND)$PULSE(C), XCROP(T,C, LAND,FERTL,TECHL)) = PULSEA(T) |
| ACROP(C,T) | SUM((FERTL,TECHL,LAND), XCROP(T,C, LAND,FERTL,TECHL)) = TCROPA(C,T) |
| TOTLABE(T) | LABDEM(T) = SUM(S,FLABONF(T,S)) + SUM(S,HIREDL(T,S)) |
| CARELAG(T,LAND) | PARECON(T,LAND) = CARECON(T,LAND) – CARECON(T – 1,LAND) |
| LABMANE(T) | TLABMAN(T) = MANURL*0.001*MANUSE(T) |
| LABMAN2(T) | TLABMAN(T) = SUM(S,LABMAN(T,S)) |
| LABCULT(T) | LABFARM(T) = LABDEM(T) – TLABCONS(T) |
| LABRCONE(T) | TLABRCON(T) = SUM(LAND,CONSREM(T,LAND) *CONSERL(LAND,‘LREMCON’)) |
| TFLABONF(T) | TFLABON(T) = SUM(S,FLABONF(T,S)) |
| TFLABOF(T) | TFLABOFF(T) = SUM(S,FLABOFM(T,S)) |
| TFLEISR(T) | TLEISURE(T) = SUM(S,FLEISURE(T,S)) |
| THIRLAB(T) | THIREDL(T) = SUM(S,HIREDL(T,S)) |
| TLBCON(T) | TLABCONS(T) = SUM(S,LABCON(T,S)) |
| TLBRCON(T) | TLABRCON(T) = SUM(S,LABRCON(T,S)) |
| TFLAHOX(T) | TFLABHOX(T) = SUM(S,FLABOXH(T,S)) |

### Land Renting by Soil Category

| | |
|---|---|
| REGHIRE(T) | HIREIREG(T) = SUM(LAND,HIRINL(T,LAND) $REGOSOL(LAND)) |
| ANDHIRE(T) | HIREIAND(T) = SUM(LAND,HIRINL(T,LAND) $ANDOSOL(LAND)) |
| LAROTL(T) | RENTUTL(T) = SUM(LAND,RENTOUT(T,LAND)) |

# APPENDIX B

# Seasonality and Labor Allocation in the Model: Example Output for Model Validation

### Shadow Value of Leisure (birr per man-day) by Season and Year (Variable SVALUELS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6.065 | 3.616 | 4.399 | 8.498 | 9.031 | 6.141 | 3.914 | 4.699 | 5.144 | 7.080 |
| 2 | 5.842 | 3.000 | 3.817 | 8.533 | 9.066 | 5.791 | 3.568 | 4.351 | 4.795 | 6.851 |
| 3 | 6.064 | 3.000 | 3.873 | 8.620 | 9.505 | 5.937 | 3.715 | 4.497 | 4.942 | 7.079 |
| 4 | 5.897 | 3.000 | 3.484 | 8.620 | 9.429 | 5.715 | 3.491 | 4.274 | 4.719 | 6.908 |
| 5 | 5.416 | 3.000 | 3.272 | 8.311 | 8.840 | 5.235 | 3.000 | 3.774 | 4.228 | 6.417 |

### Total Crop Labor by Season (Variable CROPLABS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 28.513 | 10.360 | 5.026 | 32.696 | 17.777 | 4.024 | 17.770 | 21.604 | 9.068 | 14.453 |
| 2 | 27.368 | 9.631 | 4.184 | 30.828 | 15.226 | 4.228 | 16.494 | 22.279 | 8.897 | 13.422 |
| 3 | 29.784 | 11.993 | 5.795 | 24.708 | 14.055 | 4.411 | 15.090 | 16.130 | 11.778 | 17.038 |
| 4 | 23.082 | 9.993 | 5.771 | 20.997 | 12.841 | 4.008 | 12.303 | 14.182 | 10.937 | 14.360 |
| 5 | 17.817 | 7.223 | 6.932 | 19.465 | 11.721 | 4.324 | 10.364 | 17.086 | 9.775 | 11.612 |

### Livestock Labor by Season (Variable LVSTLABS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 20.259 | 22.012 | 46.294 | 25.518 | 25.518 | 22.012 | 20.259 | 20.259 | 20.259 | 20.259 |
| 2 | 20.041 | 21.721 | 45.205 | 25.082 | 25.082 | 21.721 | 20.041 | 20.041 | 20.041 | 20.041 |
| 3 | 19.838 | 21.451 | 44.191 | 24.676 | 24.676 | 21.451 | 19.838 | 19.838 | 19.838 | 19.838 |
| 4 | 19.670 | 21.226 | 43.348 | 24.339 | 24.339 | 21.226 | 19.670 | 19.670 | 19.670 | 19.670 |
| 5 | 19.230 | 20.639 | 41.148 | 23.459 | 23.459 | 20.639 | 19.230 | 19.230 | 19.230 | 19.230 |

## On-Farm Labor by Season (Variable ONFLABS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 48.772 | 32.371 | 91.073 | 58.213 | 43.295 | 26.036 | 38.029 | 41.863 | 29.327 | 34.712 |
| 2 | 47.409 | 33.756 | 64.660 | 55.910 | 40.308 | 25.950 | 36.535 | 42.320 | 28.938 | 33.463 |
| 3 | 49.622 | 33.444 | 94.416 | 49.384 | 38.731 | 25.861 | 34.928 | 35.968 | 31.617 | 36.877 |
| 4 | 42.752 | 31.219 | 117.408 | 45.336 | 37.180 | 25.234 | 31.972 | 33.852 | 30.607 | 34.029 |
| 5 | 37.047 | 36.245 | 115.750 | 42.924 | 35.180 | 24.963 | 29.593 | 36.316 | 29.004 | 30.842 |

## Labor Used for Removal of Conservation in Each Season (man-days) (Variable LABRCON.L)

| Year | March–May |
|---|---|
| 1 | 19.450 |

## Labor Used for Conservation in Each Season (man-days) (Variable LABCON.L)

| Year | February | March–May |
|---|---|---|
| 1 | | 0.840 |
| 2 | | 0.130 |
| 3 | | 30.026 |
| 4 | | 59.134 |
| 5 | 0.766 | 67.670 |

## Labor Used for Manure Distribution in Each Season (man-days) (Variable LABMAN.L)

| Year | February | March–May |
|---|---|---|
| 1 | | 19.462 |
| 2 | 2.404 | 15.141 |
| 3 | | 14.404 |
| 4 | | 9.155 |
| 5 | 7.617 | |

## Off-Farm Family Labor Used in Each Season (man-days) (Variable FLABOFM.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.540 | 5.134 | 35.664 | 1.382 | 41.786 | 24.604 | 1.385 | 1.994 | 16.779 | 19.732 |
| 2 | 3.114 | | 54.576 | 5.236 | 22.668 | 24.342 | 1.545 | 0.662 | 16.484 | 21.373 |
| 3 | 3.132 | 1.122 | 28.778 | 13.541 | 27.248 | 26.316 | 5.083 | 8.893 | 15.679 | 20.209 |
| 4 | 10.488 | 4.177 | 0.523 | 19.099 | 30.120 | 27.136 | 7.391 | 10.755 | 16.598 | 23.713 |
| 5 | 15.075 | | | 21.890 | 31.617 | 26.212 | 6.652 | 6.061 | 16.383 | 26.110 |

### Family Leisure Time in Each Season (man-days) (Variable FLEISURE.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.699 | 18.974 | 60.353 | 0.414 | 2.155 | 16.430 | 10.006 | 12.622 | 13.904 | 12.626 |
| 2 | 10.928 | 24.079 | 72.345 | 0.304 | 2.088 | 18.388 | 12.526 | 14.854 | 16.028 | 13.843 |
| 3 | 10.171 | 24.657 | 72.984 | | 0.648 | 18.151 | 11.809 | 14.363 | 15.630 | 13.243 |
| 4 | 11.195 | 25.249 | 82.956 | | 0.925 | 19.646 | 13.701 | 16.039 | 17.231 | 14.274 |
| 5 | 13.859 | 25.855 | 89.958 | 1.167 | 3.066 | 22.569 | 18.092 | 19.724 | 20.595 | 16.792 |

### Total Family Labor Available in Each Season (Variable TFLABS)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 60.010 | 56.480 | 187.090 | 60.010 | 63.540 | 67.070 | 49.420 | 56.480 | 60.010 | 67.070 |
| 2 | 61.450 | 57.836 | 191.580 | 61.450 | 65.065 | 68.680 | 50.606 | 57.836 | 61.450 | 68.680 |
| 3 | 62.925 | 59.224 | 196.178 | 62.925 | 66.627 | 70.328 | 51.821 | 59.224 | 62.925 | 70.328 |
| 4 | 64.435 | 60.645 | 200.886 | 64.435 | 68.226 | 72.016 | 53.064 | 60.645 | 64.435 | 72.016 |
| 5 | 65.982 | 62.100 | 205.708 | 65.982 | 69.863 | 73.744 | 54.338 | 62.100 | 65.982 | 73.744 |

### Total Seasonal Family Labor Use (Variable TFLAB.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 50.311 | 37.506 | 126.737 | 59.596 | 61.385 | 50.640 | 39.414 | 43.858 | 46.106 | 54.444 |
| 2 | 50.523 | 33.756 | 119.235 | 61.146 | 62.977 | 50.291 | 38.080 | 42.982 | 45.422 | 54.836 |
| 3 | 52.754 | 34.566 | 123.194 | 62.925 | 65.979 | 52.177 | 40.011 | 44.861 | 47.295 | 57.085 |
| 4 | 53.240 | 35.396 | 117.931 | 64.435 | 67.301 | 52.370 | 39.364 | 44.606 | 47.204 | 57.742 |
| 5 | 52.122 | 36.245 | 115.750 | 64.814 | 66.797 | 51.175 | 36.245 | 42.376 | 45.387 | 56.952 |

### Seasonal Oxen Labor Use (Variable OXLABS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14.026 | 11.354 | 1.938 | 17.000 | 17.596 | 0 | 12.183 | 7.712 | 4.434 | 10.997 |
| 2 | 12.929 | 10.051 | 1.696 | 17.000 | 15.724 | 0 | 10.288 | 6.383 | 6.249 | 10.837 |
| 3 | 16.937 | 15.645 | 3.312 | 13.145 | 13.206 | 0 | 9.595 | 5.696 | 2.436 | 9.833 |
| 4 | 14.937 | 14.323 | 3.283 | 10.579 | 11.282 | 0 | 9.140 | 5.473 | 2.436 | 6.917 |
| 5 | 15.495 | 11.126 | 4.444 | 10.071 | 9.486 | 0 | 8.503 | 5.433 | 2.040 | 5.379 |

### Seasonal Oxen Labor Capacity (Variable OXCAPS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 19.400 | 18.400 | 53.000 | 17.000 | 20.700 | 19.000 | 14.000 | 18.400 | 17.000 | 21.700 |
| 2 | 19.400 | 18.400 | 53.000 | 17.000 | 20.700 | 19.000 | 14.000 | 18.400 | 17.000 | 21.700 |
| 3 | 19.400 | 18.400 | 53.000 | 17.000 | 20.700 | 19.000 | 14.000 | 18.400 | 17.000 | 21.700 |
| 4 | 19.400 | 18.400 | 53.000 | 17.000 | 20.700 | 19.000 | 14.000 | 18.400 | 17.000 | 21.700 |
| 5 | 17.000 | 16.000 | 53.000 | 17.000 | 18.000 | 19.000 | 14.000 | 16.000 | 17.000 | 19.000 |

## Seasonal Oxen Leisure (Variable OXLEIS.L)

| Year | January | February | March–May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.374 | 7.046 | 51.062 | | 3.104 | 19.000 | 1.817 | 10.688 | 12.566 | 10.703 |
| 2 | 6.471 | 8.349 | 51.304 | | 4.976 | 19.000 | 3.712 | 12.017 | 10.751 | 10.863 |
| 3 | 2.463 | 2.755 | 49.688 | 3.855 | 7.494 | 19.000 | 4.405 | 12.704 | 14.564 | 11.867 |
| 4 | 4.463 | 4.077 | 49.717 | 6.421 | 9.418 | 19.000 | 4.860 | 12.927 | 14.564 | 14.783 |
| 5 | 1.505 | 4.874 | 48.556 | 6.929 | 8.514 | 19.000 | 5.497 | 10.567 | 14.960 | 13.621 |

# References


Angelsen, A., J. B. Aune, S. Glomsrød, and S. Holden. 2003. Carbon leakage in CDM projects: Here, there and everywhere? Unpublished manuscript. Department of Economics and Resource Management, Agricultural University of Norway.

Barbier, B. 1996. *Impact of Market and Population Pressure on Production, Incomes and Natural Resources in the Dryland Savannas of West Africa: Bio-Economic Modeling at the Village Level.* ETPD Discussion Paper No. 21. Washington, D.C.: International Food Policy Research Institute.

———. 1998. Induced innovation and land degradation: Results from a bio-economic model of a village in West Africa. *Agricultural Economics* 19: 15–25.

Barbier, B., and G. Bergeron. 1998. *Natural Resource Management in the Hillsides of Honduras: Bio-economic Modeling at the Micro-Watershed Level.* ETPD Discussion Paper No. 32. Washington, D.C.: International Food Policy Research Institute.

———. 1999. Impact of policy interventions on land management in Honduras: Results of a bio-economic model. *Agricultural Systems* 60: 1–16.

———. 2001. *Natural Resource Management in the Hillsides of Honduras. Bio-economic Modeling at the Micro-watershed Level.* Research Report No. 123. Washington, D.C.: International Food Policy Research Institute.

Barrett, C., S. Holden, and D. Clay. 2004. Can food-for-work programs reduce vulnerability? In *Insurance Against Poverty,* ed. S. Dercon. Oxford: Oxford University Press.

Binswanger, H. P. 1980. Attitudes toward risk: Experimental measurement in rural India. *American Journal of Agricultural Economics* 62: 395–407.

———. 1981. Attitudes toward risk: Theoretical implications of an experiment in rural India. *The Economic Journal* 91: 867–890.

———. 1982. Empirical estimation and use of risk preferences: Discussion. *American Journal of Agricultural Economics* 64: 391–393.

Binswanger, H., and M. R. Rosenzweig. 1986. Behavioral and material determinants of production relations in agriculture. *Journal of Development Studies* 22: 503–539.

Binswanger, H. P., and D. A. Sillers. 1983. Risk aversion and credit constraints in farmers' decision-making: A reinterpretation. *Journal of Development Studies* 20: 5–21.

Binswanger, H., J. McIntire, and C. Udry. 1989. Production relations in semi-arid African agriculture. In *The Economic Theory of Agrarian Institutions,* ed. P. Bardhan. Oxford: Clarendon Press.

Boserup, E. 1965. *The Conditions of Agricultural Growth. The Economics of Agrarian Change under Population Pressure.* London: Earthscan Publications.

Boucher, S., and M. R. Carter. 2001. *Risk Rationing and Activity Choice in Moral Hazard Constrained Credit Markets.* Staff Paper No. 445, Department of Agricultural and Applied Economics, University of Wisconsin at Madison.

Chayanov, A. V. 1966. *The Theory of Peasant Economy,* eds. D. Thorner, B. Kerblay, and R. E. F. Smith. Homewood, Ill., U.S.A.: Irwin.

Clark, C., and M. Haswell. 1970. *The Economics and Subsistence Agriculture.* New York: St. Martin's Press.

Cruces, G., and Q. Wodon. 2003. Risk-Adjusted Poverty in Argentina: Measurement and Determinants. Presented at WIDER conference on Inequality, Poverty and Human Well-Being, May 30–31, Helsinki.

De Janvry, A., M. Fafchamps, and E. Sadoulet. 1991. Peasant household behaviour with missing markets: Some paradoxes explained. *Economic Journal* 101: 1400–1417.

Fan, S., and P. Hazell. 2000. Are returns to public investment lower in less-favored rural areas? An empirical analysis of India. *Economic and Political Weekly* (April 22): 1455–1463.

Feder, G. 1985. The relationship between farm size and farm productivity: The role of family labour, supervision, and credit constraints. *Journal of Development Economics* 18: 297–313.

Hazell, P., R. Ruben, H. Jansen, and A. Kuyvenhoven. 2002. Investing in poor people in poor lands. Paper prepared for the International Fund for Agricultural Development, IFPRI, Washington, D.C., and Wageningen University and Research Center, Wageningen, The Netherlands.

Holden, S. T. 1993a. Peasant household modelling: Farming systems evolution and sustainability in northern Zambia. *Agricultural Economics* 9: 241–267.

———. 1993b. The potential of agroforestry in the high rainfall areas of Zambia: A peasant programming model approach. *Agroforestry Systems* 24: 39–55.

———. 2004. Bio-economic modelling approaches for natural resource management impact assessment. In *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts,* eds. B. Shiferaw, H. Ade Freeman, and S. Swinton. Cambridge, Mass., U.S.A.: CABI Publishing, pp. 175–196.

Holden, S. T., and H. Binswanger. 1998. Small-farmer decisionmaking, market imperfections, and natural resource management in developing countries. In *Agriculture and the Environment. Perspectives on Sustainable Rural Development,* eds. E. Lutz, H. Binswanger, P. Hazell, and A. McCalla. Washington, D.C.: The World Bank.

Holden, S. T., and H. Lofgren. 2004. Assessing the impacts of natural resource management policy interventions with a village general equilibrium model. In *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts,* eds. B. Shiferaw, H. Ade Freeman, and S. Swinton. Cambridge, Mass., U.S.A.: CABI Publishing, pp. 295–318.

Holden, S. T., and B. Shiferaw. 2000. Development paths and policies for sustainable land management in Andit Tid, North Shewa. An exploration of policy alternatives. Presented at the national workshop on "Policies for Sustainable Land Management," May 22–23, Addis Ababa.

Holden, S. T., and H. Yohannes. 2002. Land redistribution, tenure insecurity, and intensity of production: A study of farm households in Southern Ethiopia. *Land Economics* 78(4): 573–591.

Holden, S. T., B. Shiferaw, and M. Wik. 1998. Poverty, market imperfections, and time preferences: Of relevance for environmental policy? *Environment and Development Economics* 3: 105–130.

Holden, S. T., B. Shiferaw, and J. Pender. 2001. Market imperfections and profitability of land use in the Ethiopian highlands. *Journal of Agricultural Economics* 52: 3, 53–70.

———. 2004. Non-farm income, household welfare and sustainable land management in a less-favoured area in the Ethiopian highlands. *Food Policy* 29: 369–392.

Holden S. T., S. Benin, B. Shiferaw, and J. Pender. 2003. Tree planting for poverty reduction in less-favoured areas of the Ethiopian highlands. *Small-Scale Forest Economics, Management and Policy* 2(1): 63–80.

Holden, S. T., C. Barrett, and F. Hagos. 2005. Food-for-work for poverty reduction and promotion of sustainable land use: Can it work? *Environment and Development Economics,* in press.

Hurni, H. 1993. Land degradation, famines and resource scenarios in Ethiopia. In *World Soil Erosion and Conservation,* ed. D. Pimentel. Cambridge: Cambridge University Press.

Jagger, P., and J. Pender. 2003. The role of trees for sustainable management of less-favored lands: The case of eucalyptus in Ethiopia. *Forest Policy and Economics* 3(1): 83–95.

Kruseman, G. 2000. *Bio-economic Household Modelling for Agricultural Intensification.* PhD dissertation, Wageningen University, Wageningen.

Leibenstein, H. 1957. Underemployment in backward economies. *Journal of Political Economy* 65: 91–103.

———. 1958. Underemployment in backward economies: Some additional notes. *Journal of Political Economy* 66: 256–258.

Lewis, W. A. 1954. Economic development with unlimited supplies of labour. *Manchester School of Economic and Social Studies* 22: 139–191.

Lipsey, R. G., and K. Lancaster. 1956. The general theory of second best. *Review of Economic Studies* 24(1): 11–32.

Ludi, E. 1997. *Household and Communal Strategies: Small-scale Farming Families and Their Options for Self-Employment. A Case Study in Anjeni, Ethiopia.* Research Report 30. Soil Conservation Research Programme, University of Bern, Switzerland, in association with the Ministry of Agriculture, Ethiopia.

Malthus, T. 1987. *An Essay on the Principles of Population.* The version published in 1803, with variations of 1806, 1807, 1817, and 1826. Volume I, ed. P. James. Cambridge: Cambridge University Press.

Nakajima, C. 1986. *Subjective Equilibrium Theory of the Farm Household.* Amsterdam: Elsevier.

Okumu, B., M. Jabbar, D. Colman, and N. Russell. 2002. A bio-economic model of integrated crop-livestock farming systems: The case of the Ginchi Watershed in Ethiopia. In *Natural Resources Management in African Agriculture,* eds. C. B. Barrett, F. Place, and A. A. Aboud. Cambridge, Mass., U.S.A.: CABI Publishing.

Pender, J., and P. Hazell, eds. 2000. *Promoting Sustainable Development in Less-Favored Areas.* 2020 Vision, Focus 4. Washington, D.C.: International Food Policy Research Institute.

Pender, J., F. Place, and S. Ehui. 1999. *Strategies for Sustainable Agricultural Development in the East African Highlands.* Discussion Paper No. 41. Environment and Production Technology Division. Washington, D.C.: International Food Policy Research Institute.

Pender, J., B. Gebremedhin, S. Benin, and S. Ehui. 2001. Strategies for sustainable agricultural development in the Ethiopian highlands. *American Journal of Agricultural Economics* 83(5): 1231–1240.

Ray, D. 1998. *Development Economics.* Princeton: Princeton University Press.

Ruben, R., A. Kuyvenhoven, and G. Kruseman. 2001. Bioeconomic models and ecoregional development: Policy instruments for sustainable intensification. In *Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment,* eds. D. R. Lee and C. B. Barrett. Cambridge, Mass., U.S.A.: CABI Publishing.

Sadoulet, E., and A. de Janvry. 1995. *Quantitative Development Policy Analysis.* Baltimore: The Johns Hopkins University Press.

Shiferaw, B., and S. T. Holden. 1998. Resource degradation and adoption of land conservation technologies in the Ethiopian highlands: A case study in Andit Tid, North Shewa. *Agricultural Economics* 18: 233–247.

———. 1999. Soil erosion and smallholders' conservation decisions in the highlands of Ethiopia. *World Development* 27(4): 739–752.

———. 2000. Policy instruments for sustainable land management: The case of highland smallholders in Ethiopia. *Agricultural Economics* 22: 217–232.

———. 2001. Farm level benefits to investments for mitigating land degradation: Empirical evidence from Ethiopia. *Environment and Development Economics* 6: 335–358.

———. 2004. Assessing the economic and environmental impacts of conservation technologies and poverty-investment linkages: A farm-level bio-economic modeling approach. In *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts,* eds. B. Shiferaw, H. Ade Freeman, and Scott Swinton. Cambridge, Mass., U.S.A.: CABI Publishing, pp. 269–294.

Shiferaw, B., S. T. Holden, and J. Aune. 2000. Population pressure, poverty and incentives for soil conservation in Ethiopia: A bio-economic modeling approach. Presented at the Second International Conference on Environment and Development, September 6–8, Stockholm.

———. 2001. Population pressure and land degradation in the Ethiopian highlands: A bio-economic model with endogenous soil degradation. In *Economic Policy Reforms and Sustainable Land Use: Recent Advances in Quantitative Analysis for Developing Countries,* eds. N. Heerink, H. van Keulen, and M. Kuiper. Heidelberg: Springer-Verlag.

Singh, I., L. Squire, and J. Strauss, eds. 1986. *Agricultural Household Models: Extensions, Applications and Policy.* Washington, D.C., and Baltimore: The World Bank and The John Hopkins University Press.

Stoorvogel, J. J., and E. M. A. Smaling. 1990. *Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983–2000,* Volume I: Main Report. Wageningen: The Winand Staring Centre.

Vosti, S., J. Witcover, and C. L. Carpentier. 2002. *Agricultural Intensification by Smallholders in the Western Brazilian Amazon. from Deforestation to Sustainable Land Use.* Research Report No. 130. Washington, D.C.: International Food Policy Research Institute.

Wik, M., T. K. Aragie, O. Bergland, and S. T. Holden. 2004. On the measurement of risk aversion from experimental data. *Applied Economics* 36: 2443–2451.

Yohannes, G. 1989. *Land-Use, Agricultural Production and Soil Conservation Methods in the Andit Tid Area, Shewa Region.* Research Report 17. Soil Conservation Research Project, Ministry of Agriculture Soil and Water Conservation Development, Addis Ababa.