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Agricultural Economics 30 (2004) 31–49

AGRICULTURAL ECONOMICS

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Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: a bio-economic model with market imperfections

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Received 14 August 2002; accepted 2 September 2002

Abstract

This paper presents a bio-economic model of Andit Tid, a severely degraded crop–livestock farming system with high population density and good market access in the highlands of Ethiopia. Land degradation, population growth, stagnant technology, and drought threaten food security in the area. Drought or weather risk appears to have increased in recent years. The bio-economic model is used to analyse the combined effects of land degradation, population growth, market imperfections and increased risk of drought on household production, welfare and food security. We find that the indirect effects of drought on household welfare through the impact on crop and livestock prices are larger than the direct production effects of drought. Provision and adoption of credit for fertiliser, although risky in itself, may lead to increased grain production and improved household welfare and food security. Provision of credit may have a negative effect on conservation incentives but this effect may be mitigated by linking a conservation requirement to the provision of credit for fertiliser.

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JEL classification: O13; Q21; Q12; Q18; Q27

Keywords: Drought; Food security; Land degradation; Market imperfections; Credit; Bio-economic modelling

1. Introduction

Land degradation, poverty and food insecurity are pervasive and interconnected problems in Ethiopia. Stochastic rainfall causes severe droughts at irregular intervals and these droughts threaten the lives and livelihoods of millions of people. Policies and technologies that can contribute to increased food production and improved food security are badly needed.

There is a growing interest in using bio-economic models as a tool for policy analysis in order to better understand pathways of development[2] and to assess the impact of alternative policies on the natural resource base and human welfare. One of the potential great benefits of these models is that they can provide an improved and more comprehensive indication of the feedback effects between human activity and natural resources. Modern computer power permits the

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[2] A pathway of development is defined as a common pattern of change (or stagnation) in agriculture and livelihood strategies, associated with causal and conditioning factors (Pender et al., 1999).

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doi:10.1016/j.agecon.2002.09.001

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 optimisation in production and consumption with inter-temporal environmental feedbacks, allowing for non-linearities in constraints as well as the objective function. Some other bio-economic models have not been truly dynamic because they have incorporated future impacts through sustainability constraints or user costs only (Holden, 1993a,b; Kruseman, 2000; Shiferaw and Holden, 1999, 2000). This model is dynamic, the households maximise discounted utility over a limited time horizon.

Market imperfections and heterogeneity of resources across households in the study area cause land use at the plot level to depend on household resources (Holden et al., 2001). Models are therefore developed for different household categories. The models are calibrated and aggregated 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 labour, a constrained rental market for land through share tenancy, oxen rental market through exchange with labour only, constrained access to formal credit in kind (for fertiliser) or to informal credit at a high interest rate.

This version of the model also incorporates risk averse behaviour through a constant partial relative risk aversion utility function, production risk due to drought, and downside risk aversion to taking credit for fertiliser. Drought also affects prices for crops and livestock and price expectations and these have additional effects on household production and welfare.

Earlier optimisation models were also criticised for being linear while the reality they were supposed to represent was highly non-linear. While piece-wise linear representations of non-linear relationships may serve as good and efficient approximations, recent advances that allow for large non-linear optimisation models increase credibility.

Like the Ginchi model (Okumu et al., 1999, 2000), this model endogenises the effects of land degradation in the form of soil erosion and nutrient depletion. 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 as well as fertiliser and manure use are endogenous decisions that affect the rate of land degradation. These decisions affect erosion and nutrient depletion rates that determine crop productivity in later years.

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, which was rare in the past. The objective of this article is to analyse the implications of this new increased production risk using the dynamic bio-economic model. Specifically, we assess:

(a) how risk of drought in combination with land degradation and population growth affects household production, income, welfare and food security; and
(b) the impact of credit for fertiliser on household welfare, food security, incentives to conserve land and soil erosion.

In Section 2 of the paper, we give a brief description of the case study area. The basic structure of the bio-economic model is outlined in Section 3, followed by a discussion of the methodology of bio-economic modelling in Section 4. The results and discussion are presented in Section 5, followed by the conclusion.

2. Description of the case study area and data

Andit Tid is located approximately 60 km north of Debre Berhan, along the main road between Addis Ababa and the Tigray Region, in North 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 (>3000 m.a.s.l.). The land is located in two altitude zones; *dega* zone (<3200 m.a.s.l.) and *wurch* zone (>3200 m.a.s.l.). The average rainfall is 1336 mm per year distributed over two growing seasons, the *meher*

Table 1
Farm areas by zone and slope class in Andit Tid (2000)

Land type	Depth class (cm)	Total area (ha)	Percent 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

Source: Own survey data.

season from June to November and the *belg* season from January to May. Droughts have not been common in the area until very lately, when the *belg* rains have failed in two consecutive years (1999 and 2000). Hailstorms and frost have, however, commonly 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 due to the high elevation. The grass turf is collected in heaps and burnt[3] before planting of barley. This releases nutrients for the crop but also causes considerable losses of organic matter and soil nitrogen. Yohannes (1989) estimated 75% of the land to be on steep slopes (>25% slope). Soil erosion rates in the area are very high and a large share of the land is shallow, causing reduction of soil depth to affect crop rooting depth and thus yields (Shiferaw and Holden, 2001). Holden and Shiferaw (2000) estimated 21% of the agricultural land to be shallow (<30 cm soil depth) and 48% to be of medium depth (30–60 cm) (Table 1). Based on the survey data, we divided land into eight land classes for our modelling (Table 2).

Various forms of conservation technologies are common in the area. They have partly been introduced through external food-for-work programs. Exogenously introduced conservation structures have later been partly removed by the farmers. 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 harbour rats that might damage crops.

The main crop in the area is barley, followed by wheat, horse bean and field pea. Lentils and linseeds are also commonly grown. Most crop production takes place in the *dega* zone but barley is also grown in the *wurch* zone in the *belg* season. The high elevation prevents production of other crops in this zone.

Cattle and sheep are the dominant types of livestock, but goats, equines and chicken are also common (Table 2). The animal population density is very high in the area; Yohannes (1989) estimated it to be 1.48 tropical livestock units per hectare (TLU/ha) against 0.36 as the average for the Ethiopian highlands (Table 3). We found this density to have increased to 2.03 TLU/ha in 1998 but it declined to 1.71 TLU/ha by the end of 1999 due to the drought (Holden and Shiferaw, 2000).

The human population density was estimated to be 145.5 persons/km^2 in 1986 against the average of 61 persons/km^2 for the Ethiopian highlands (Yohannes, 1989). The population density was 230 persons/km^2 cultivable land. The population growth rate was estimated to be 3% per year, indicating that population pressure in the area is increasing.

Production of crops and livestock are well integrated 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 fertiliser 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%) is from communal land. There is, however, free grazing outside the cropping season and this may create incentives for overstocking of animals. Fodder shortage is an important constraint and purchase of fodder and the use of cut and carry system are the main strategies to overcome this problem besides limiting the number of animals kept (Holden and Shiferaw, 2000).

[3] Locally called *gaay*.

Table 2
Basic household and farm characteristics for household groups in 1999, used as input in the model

Variable	Household group		
	More than two oxen	One ox	No ox
Household size (persons)	6.44	5.81	4.1
Work force (persons)	3.53	2.89	2.2
Consumer units (persons)	5.15	4.54	3.31
Land owned by land type (ha)			
Regosols, slope 0–20%, depth 25 cm	0.79	0.69	0.50
Regosols, slope 0–20%, depth 45 cm	0.41	0.36	0.26
Regosols, slope 0–20%, depth 60 cm	0.15	0.13	0.10
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	0.10
Andosols, slope >20%, depth 25 cm	0.12	0.10	0.07
Total farm size (ha)	2.68	2.36	1.70
Livestock ownership (number)			
Oxen	2.00	1.00	0.00
Cows	1.00	0.69	0.50
Bulls	0.38	0.34	0.20
Heifers	0.58	0.21	0.10
Sheep, ewes	3.71	2.63	1.07
Sheep, ram	1.63	0.82	0.07
Goat, doe	0.77	0.32	0.07
Goat, buck	0.29	0.13	0.00
Hen	2.00	2.00	2.00

Source: Own data.

The land resources (land of different qualities) are fairly evenly distributed among households in the area due to the land reform and frequent land redistributions whereby land was allocated to households based on household size. Livestock wealth is therefore a better indicator of household wealth and wealth differentiation. Particularly oxen ownership signifies the farming capacity of households as the rental market for oxen (ploughing) is imperfect (Holden and Shiferaw, 2000). It also leads to the typical pattern where households without oxen rent out land to households with two oxen or more, while households with one ox exchange oxen among themselves.

Table 3
Changes in Andit Tid 1986–1999

Variable	1986	1999
Average farm size (ha)	3.77	2.16
Average household size (persons)	5.04	5.67
Average oxen holding (number)	1.54	1.20
Average number of cows (number)	1.18	0.80
Average number of sheep (number)	6.25	5.30
Cereal production	Net sellers	Net buyers
Animal density (TLU/ha)	1.48	1.71

Sources: Yohannes (1989), and own data.

Land renting typically takes the form of share tenancy, where 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 fertilisers but are reluctant to take this credit even though it appears profitable. Production and market risk and high aversion to these types of risk cause households to be reluctant to buy fertiliser on credit.

Households have limited access to off-farm income sources and crop production is highly subsistence oriented, but the trend during the last 20 years has been from households being net sellers of food grains to now being net buyers. The recent droughts have even transformed the area to become dependent on food aid (Holden and Shiferaw, 2000).

The site selected for this study is unique in the African context due to the detailed biophysical and socio-economic data available over a period of 15–20 years. The biophysical data include:

- detailed soil physical and chemical data;
- erosion data at the plot level for different conservation technologies and crops over several years (from researcher managed and farmer managed experiments and farmers' plots);
- crop yield data on different soils and under different conservation technologies;
- climatic data; and
- 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 1 summarises the plot level data by soil/climatic zone and soil depth.

Erosion rates were estimated based on experiments carried out by SCRP[4] over many years in the study site. Yield responses were estimated based on SCRP experimental data for conservation technology responses, and based on FAO fertiliser experiments and local crop-fertiliser demonstration plots managed by the extension system. A comprehensive analysis of some of these data is presented in Shiferaw and Holden (2001).

Socio-economic data were collected in household surveys in 1986, 1994, 1998 and 2000. The three last surveys were carried out by the authors. These data were used to structure and calibrate the bio-economic models for the different household categories (Tables 1–3). Prices from 1997 (normal year) and 1999 (drought year) (Table 4) were used to construct expected prices based on the probability of drought.

Table 4
Prices (Birr/kg) of crops and livestock (Birr per animal) in 1997 (normal year) and 1999 (drought year)

Crop or livestock type	Price in 1997	Price in 1999
Barley, meher	1.05	1.65
Barley, belg	0.83	1.42
Wheat	1.66	2.35
Field pea, meher	2.15	2.37
Field pea, belg	2.15	2.08
Horse bean	1.67	2.38
Lentil, meher	2.41	3.66
Lentil, belg	2.41	3.75
Linseed	1.66	3.00
Oxen	966	585
Cows	558	460
Bulls	500	293
Heifers	333	237
Calves	172	68
Sheep, ewes	57	41
Sheep, ram	45	56
Lambs	33	50
Goat, doe	46	41
Goat, buck	48	54
Kids	33	40
Hen, chicken	10	7

Source: Own data.

3. The bio-economic model

Earlier versions of this model include Shiferaw et al. (2000, 2001). The main expansion of the model presented here is 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 its ability to replicate current and recent land use and household welfare in the study area.

A simple conceptual representation of the model is presented in Fig. 1. A more detailed technical description is given in Appendix A. Households maximise their welfare (measured as utility of certainty equivalent full income) subject to numerous constraints. The model is dynamic and non-linear. For example, land degradation in form of soil erosion and nutrient depletion is endogenous as it is affected by household production and investment decisions. Furthermore, soil erosion affects soil depth which in turn affects yields and output in following years that again affect income and welfare. Weather risk affects production as well as prices and this may again affect production decisions. Households make production decisions

[4] Soil Conservation Research Project (SCRP) was funded by the Swiss government and carried out soil conservation research in selected sites in the Ethiopian highlands from 1981 to the mid-1990s.

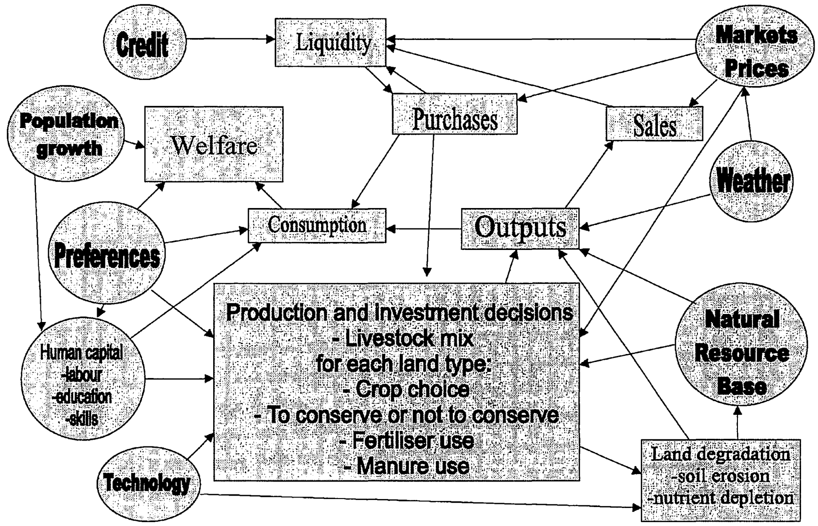


Fig. 1. Main components of bio-economic household group model.

based on expectations about prices and output and the risk involved. Imperfections in markets (limited access, high transaction costs) affect production decisions and cause non-separability of production and consumption decisions. Population growth affects both the labour force and household welfare as more people have to share the outcome of a constant land area that also is affected by land degradation. This leads to a Malthusian development path when technology, prices and other exogenous factors are constant. This poverty-environment trap can only be broken through availability of new technologies, improved access to markets and better investment opportunities.

4. Methodology

Holden et al. (2001) found that market imperfections in the study area affected land use and plot level land productivity and this has implications for how units for bio-economic modelling were identified. These findings indicate that aggregate bio-economic models at watershed and/or community levels would fail to address issues related to social differentiation and its impact on land use. Watershed or community level bio-economic models typically rely on perfect market assumptions and separability of production decisions from consumption decisions or on egalitarian distribution of resources and equal market access within communities.[5] These assumptions do not fit well with 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 the household group level, and to aggregate from (uniform) household groups to the community or watershed levels afterwards. However, our approach does not capture explicit spatial issues such as the close neighbour effects of conservation decisions (spatial externalities).

Household group modelling 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 in the different household groups may change over time, however, and this must be adjusted during aggregation in later years. Alternatively, farm sizes could be adjusted down if fragmentation of land holdings or

[5] The land reform in Ethiopia resulted in an egalitarian land distribution in most communities. However, distribution of household labour and livestock, especially oxen used for traction, is less equally distributed.

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

Crop	Household group			Two oxen household group model: predicted areas	
	0	1	2	Credit constrained	Unconstrained credit
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	0.20	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	0.00	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

Source: Own data.
[a] 1999 was a year with drought in the *belg* season, therefore no crops were planted in this season. This may have cause the shift in barley production to the *meher* season.

land redistributions takes place.[6] We have calibrated the model 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 30% larger than reported by farmers.

Collective action and open access resources or common property regimes may potentially be important in relation to the focus of our study. In our study area, most of the land has been divided and distributed to individual households. Only a small share of the fodder resources come from communal and open access land. There is also very little collective action in the area. We therefore think that the errors we commit by treating these supplies as exogenous in the model are small.

The model is validated by comparison of base runs with actual survey data for key output variables for the different household groups (Table 5).[7] The model is constructed in GAMS. A 5-year model contains about 39,600 variables and 23,300 equations, many of which are non-linear.

[6] As our model only has a time horizon of 5 years these problems are not considered important for our analysis.

[7] Eucalyptus was not included in the 5-year model presented in this paper. We have run other models, for longer time periods, that include eucalyptus, but have not included these in this paper due to size constraints. There were no meaningful changes in cropping pattern over the 5-year period and we have therefore not included information on these changes.

5. Results and discussion

5.1. Land degradation, crop productivity and impact of conservation technologies

Fig. 2 shows the yield trends over 5 years of barley on regosols on the four different land classes with and without conservation technologies when no fertiliser or manure is applied. Yields are shown for the cases when conservation structures do not reduce initial yields and when initial yields are affected negatively. We see that yields are lowest and decline most rapidly on shallow and steep soils.

In Fig. 3, 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 and without and with a fairly high level of fertiliser application, are shown. We see that yields decline slightly faster on andosols than on regosols, faster on un-conserved than on conserved land, faster on shallow soils and steep slopes, and faster when no fertiliser is used. Yields decline even on deeper soils that are conserved and receive a high level of fertiliser (55 kg N and 50 kg P_2O_5 per ha) because conservation does not eliminate soil erosion and a marginal reduction in rooting depth reduces yields.

5.2. The impacts of drought

The effects of *belg* season drought on household welfare, income per capita, crop sale, risk premium,

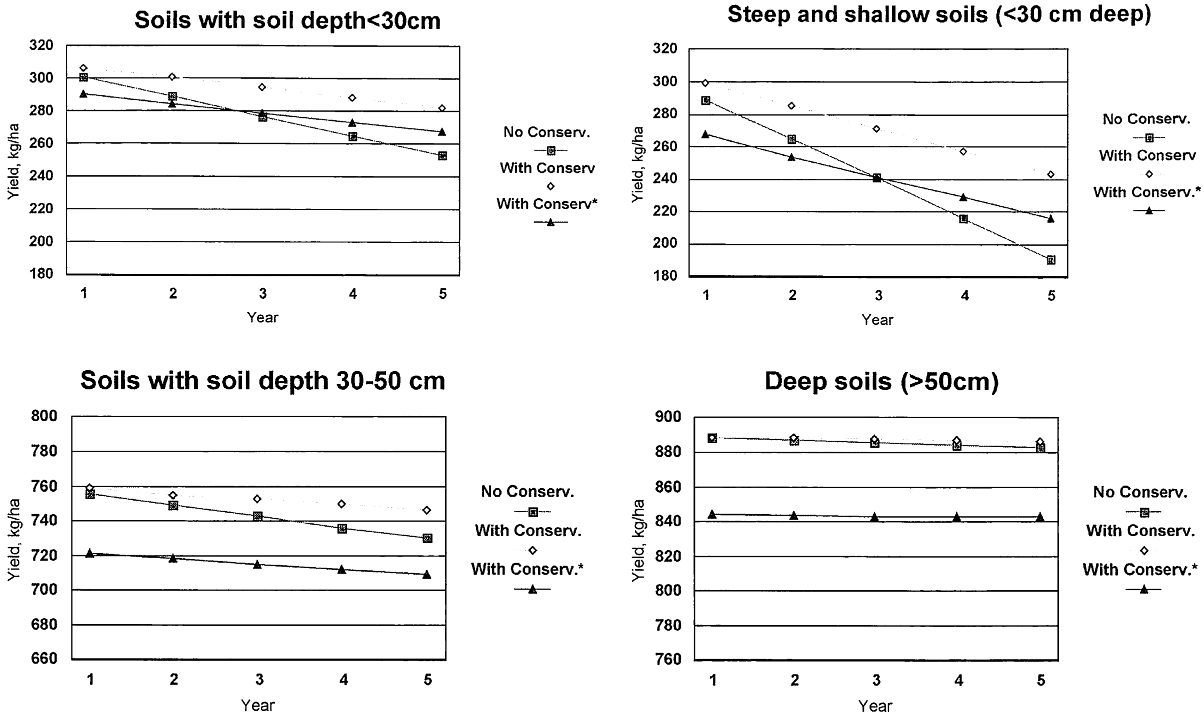


Fig. 2. Barley yields on regosols (kg/ha) with different soil depth and slope without fertiliser or manure application. *If conservation technologies reduce the yields due to their occupation of a part of the area.

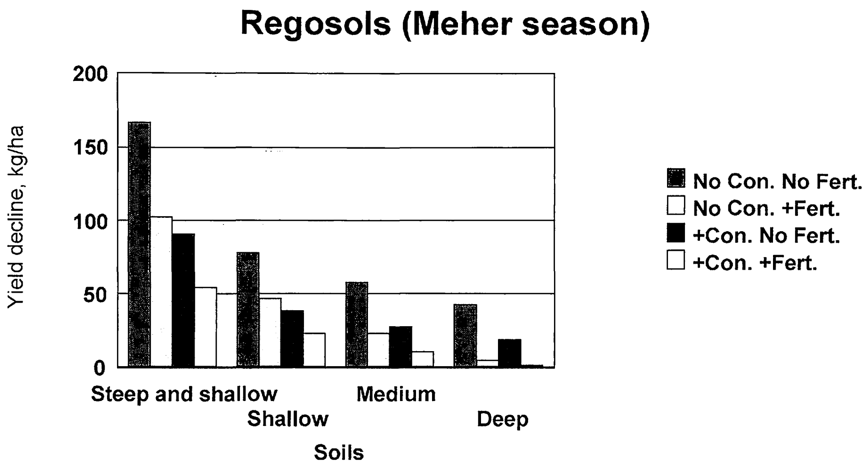
on farm labour and credit demand are presented in Table 6 for the two oxen household group. The effect of providing credit for fertiliser (unconstrained) is compared to the case when credit access is constrained. The models have been run for 10 and 20% risk of drought. We see that households with access 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. Without access to credit households are less able to do this and even become net buyers of crops in good years after a few years due to land degradation and population growth. Provision of credit and fertiliser supply may therefore to some extent reduce the need for food aid in drought years. Credit and fertiliser use helps also to better sustain household welfare while the development path is clearly Malthusian without access to credit for fertiliser (Table 6).

There are both direct and indirect effects of drought. First, there is a direct production effect as crop production is reduced due to drought. The *belg* season drought has been so severe 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 such years. This implies that they have to buy crops at a higher price. In addition, livestock prices decline when the drought is severe as people are forced to sell animals to buy food. This leads to a livestock value loss. We incorporated these losses in the model with and without access to credit and with a 10% risk of drought. The results are presented in Table 7. We see that the production loss is higher with access to credit because fertiliser is used on barley in the *belg* season in good years (no drought). The production loss tends

Table 6
Two oxen household group: impact of belg season drought on household welfare and production, when credit access for fertiliser is unconstrained or constrained

Risk of drought (%)	Year	Utility (utils)	Expected income per capita (Birr)	Net sale crops, no drought (Birr)	Net sale crops, drought (Birr)	Drought risk premium[a]	Total labour on farm (man days)	Formal credit demand (Birr)
Unconstrained access to credit for fertiliser								
10	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	−1111	0.046	434	384
20	1	0.265	541	823	−350	0.09	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 fertiliser								
10	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	−1146	0.03	405	50
	5	0.182	446	−447	−1179	0.027	405	50
20	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	−1090	0.055	396	50
	5	0.104	440	−454	−1065	0.042	410	50

[a] Drought risk premium is measured as share of poverty line income.



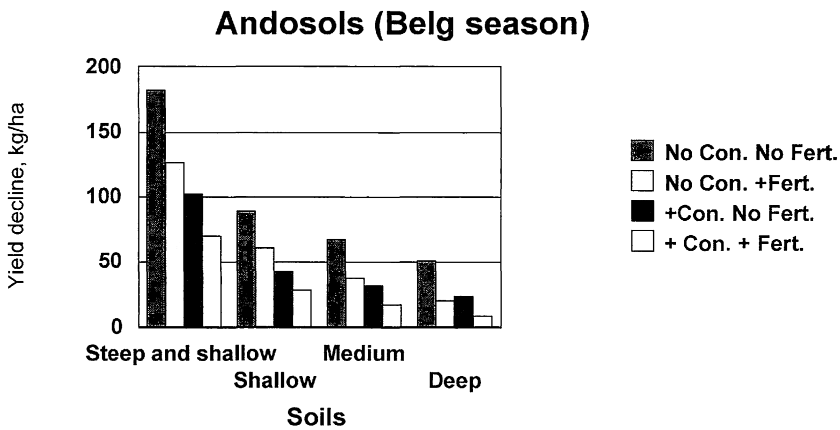


Fig. 3. Barley yield declines over 5 years on andosols and regosols, with and without fertiliser (55 kg N/ha and 50 kg P_2O_5), with and without conservation technology.

Table 7
Drought year losses and the effects of credit on drought year losses

Credit constraint	Year	Production loss[a] (Birr)	Purchase food, price loss[b] (Birr)	Livestock value loss[c] (Birr)	Total loss, (Birr)	Total loss, as share of poverty line
Yes	1	834	214	1013	2139	0.79
	2	781	415	989	2185	0.79
	3	792	471	965	2228	0.78
	4	784	651	932	2367	0.81
	5	829	689	861	2408	0.81
No	1	1321	268	1013	2679	0.99
	2	1125	313	989	2427	0.87
	3	1051	412	965	2429	0.85
	4	1043	552	920	2524	0.86
	5	1028	632	861	2558	0.86

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

Table 8
Effects of credit access on conservation investment and soil erosion when conservation technologies do not reduce initial yields

Credit constraint	Year	Total erosion (tons per farm)	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

to decline over years due mainly to crop productivity loss. The loss due to the need to buy cereals for food in drought years increases over time, however, and is not much different with or without access to credit for fertiliser. Livestock value losses decline over time as the number of animals declines over time. The total loss is around 80% of the poverty line income when credit access is constrained and even higher when credit for fertiliser is used. The direct production loss is 30–40% of the total loss without access to credit and is 40–50% of the total loss with access to credit.

5.3. Impact of credit on conservation incentives

The model includes both the options of removal of conservation structures and of building new conservation structures and there is a labour requirement for maintaining conservation structures. Earlier versions of our model were used to test how credit access and fertiliser use affected incentives to conserve land (Shiferaw et al., 2001). In Table 8, we present new results on this for the case in which conservation technologies do not reduce initial yields. The table shows that the total erosion (tons of soil per farm) is higher

Table 9
Effects of credit access and interlinkage requirements of using credit for fertiliser on conserved land only when conservation technologies take 5–10% of the land out of production

Credit constraint	Interlinked credit to conservation	Year	Utility	Total erosion (tons per farm)	Total labour (man days)	Labour for removal of conservation structures (man days)	Labour 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	0.31	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	0.58	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

after provision of credit as the area conserved is lower, particularly in the initial years. The proportion of total land conserved increases from 39 to 64% when there is no access to credit and from 29 to 62% with access to credit. There is some removal of conservation structures in the terminal year.

In Table 9, we look at the case in which 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 fertiliser is used. We see that erosion rates are higher when initial yields are reduced by conservation structures. More labour is used for removal of conservation structures in the initial year. Provision of credit does not increase erosion as much in the case in which conservation structures reduce initial yields, because conservation structures are also removed in the credit constrained case. Imposing an interlinkage (cross-compliance) policy that credit for fertiliser only is available for conserved land, reduces erosion levels by 5–15%. The reduction is largest in the initial years as less conservation structures are removed and more new structures are built. Household welfare is reduced to some extent by the interlinkage policy and total labour requirement is increased in the initial years. Household welfare improves considerably compared to the credit constrained case, however.

An important policy question is how easy or difficult it is to implement this type of interlinkage policy. There are extension agents in Andit Tid and they are already involved in promoting fertiliser use through organising 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 only gave fertiliser credit for use on flat and good soils. Few households dared to take credit for fertiliser, however, due to the risk involved. This special credit risk aversion appeared to be due to bad experience in the past when the punishment for failing to repay credit was quite severe.

6. Conclusions

We have developed a bio-economic model for a severely degraded area with high population density and good market access in the Ethiopian highlands. The area has recently been exposed to severe droughts in the *belg* season. We have developed a model to assess the impacts of the drought on household production and welfare. We use the model 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 they depend on food aid. Land degradation and population growth increase 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 wealth that households have, this indirect effect of drought is considerable. Alternative forms of storage of wealth, e.g. bank savings, should be promoted.

We find that provision of credit for fertiliser 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 *belg* season, provision of credit for fertiliser 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 drought year losses. The decline in household welfare over time may also be reduced by provision of credit for fertiliser.

Provision of credit for fertiliser 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 fertiliser 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 fertiliser use cannot sustain crop yields as erosion cannot be eliminated and soils in the area are shallow. Technical change, population control, better access to off-farm employment and out migration are necessary to avoid starvation or chronic dependence on food aid in the future.

Acknowledgements

This work is part of the IFPRI/ILRI project "Policies for Sustainable Land Management in the East African

Highlands". ILRI and IFPRI have provided funds and logistical support for the work. The Norwegian Ministry of Foreign Affairs has provided funds for this research in the Amhara Region in Ethiopia. We also draw on earlier work funded by the Research Council of Norway. We acknowledge valuable input from Jens Aune to an earlier version of the model. Valuable comments on earlier versions of the paper have been received from an anonymous reviewer and from Peter Hazell, John Pender and participants in seminars at ILRI in Addis Ababa and IFPRI in Washington, DC.

Appendix A. Detailed model description

The basic theoretical structure of the model follows. The household model represents an average household in a household group. We omit household group subscripts in the exposition below to simply notation.

Representative households (for household groups) are assumed to maximise welfare:

$$U = \int_0^T \rho^t u_t \,\mathrm{d}t = \sum_0^T \rho^t u_t \qquad \text{(A.1)}$$

through a time-separable utility function over the time horizon T. Utility in period t is discounted by the discount factor, $\rho^t = (1/(1+\delta))^t$, where δ is the utility discount rate.

Utility in period t is represented by a constant partial relative risk aversion utility function;[8]

$$u_t = (1-\mu)Y^{1-\mu} + \mu - 1 \qquad \text{(A.2)}$$

where μ is the partial relative risk aversion or the absolute value of the elasticity of marginal utility of certainty equivalent full income, Y, which is equal to:

$$Y_t = E(I_t) - \psi_{1t} - \psi_{2t} \qquad \text{(A.3)}$$

where $E(I_t)$ is expected normalised full income in period t, ψ_{1t} the downside risk premium related to obtaining formal credit and ψ_{2t} the risk premium related to drought risk in the *belg* season. Full income was normalised by the poverty line full income (γ_t), while the risk premia were normalised by the poverty line income (ζ_t),[9] excluding the value of leisure:

$$E(I_t) = \frac{E(y_t)}{\gamma_t} \qquad \text{(A.4)}$$

where $E(y_t)$ is the expected full income[10] in Ethiopian Birr in period t. Subsistence leisure, $\mathrm{Le}_{\min}$, is valued at the minimum wage rate, w_{γ_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:

$$w_{\gamma_t} = \frac{\zeta_t}{L_{\max}} \qquad \text{(A.5)}$$

where $L_{\max}$ is the maximum time available for work and ζ_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:

$$F_t = \mathrm{Le}_{\min} + L_{\max} \qquad \text{(A.6)}$$

and poverty line full income is:

$$\gamma_t = w_{\gamma_t} F_t \qquad \text{(A.7)}$$

This formulation gives utility equal to zero if the household has $Y_t = 1$, negative utility if Y_t is below the poverty line ($Y_t < 1$), and positive utility if $Y_t > 1$. Population growth affects the time endowment and poverty line income causing both 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, 1798) as a path where utility declines over time.[11] The requirement for a Boserupian development path is then that income grows faster than the population, as Y_t is a measure of per capita income in period t.

Risk premia are calibrated (Eqs. (A.8) and (A.9)) using a Taylor expansion and approximation over the utility function (Sadoulet and de Janvry, 1995):

[8] This type of utility function has been used by Binswanger (1981) and others in empirical studies of risk preferences of farm households. Its simple form makes it attractive also for modelling purposes as risk aversion is captured by a single parameter.

[9] Based on Dercon and Krishnan (1996) who develop consumption-based poverty lines for rural Ethiopia, including the study area. The poverty line is therefore treated as exogenous in the model.

[10] Computed based on probabilities of drought, hailstorm/frost damage and expected prices.

[11] The trend must be evaluated over a period of several years as it might otherwise be masked by short-term disturbances.

$$\psi_{1t} = \psi_{1t}(\mu, \mu_{\rm d}, C_{{\rm f}t}, i, \zeta_t, E(I_t)) = 0.5(\mu + \mu_{\rm d})\left[\frac{(C_{{\rm f}t}(1+i))^2}{\zeta_t}\right]E(I_t) \quad \text{(A.8)}$$

$$\psi_{2t} = \psi_{2t}(\mu, \text{var}(I_t), \zeta_t, I_t) = 0.5\mu\left[\frac{\text{var}(I_t)}{\zeta_t}\right]E(I_t) \quad \text{(A.9)}$$

where $\mu_{\rm d}$ is the additional risk aversion related to credit risk, C_t the amount of credit taken in period t, i is the interest rate, and 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.

A.1. Market characteristics

The model incorporates the following market characteristics. We leave out the subscript for year to simplify notation.

- *Credit market*: Formal credit in kind (for fertiliser) that is constrained from above (Eq. (A.10)):

$$p_{\rm f}{\rm Fe} = C_{\rm f} \leq \bar{C}_{\rm f} \quad \text{(A.10)}$$

  This credit must be repaid after harvest. It may also be possible to obtain informal credit within the village at a higher rate of interest (Eq. (A.11)):

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

  This credit must also be paid back within the same year.
- *Labour market*: Households are assumed to have constrained access to off-farm employment and the wage rate in the labour market varies across seasons. Households may also hire labour for work on the farm. A price band is introduced such that the wage rate for hiring labour, is about 10–20% higher than the wage rate obtained while working off-farm. The household shadow wage in season p, w_p^*, should fall between the buying wage and the selling wage when households do not participate in the labour market (Eq. (A.12)).

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

Households may sell labour in some seasons and buy labour in other seasons, however. The households are assumed to be drudgery averse (Chayanov, 1966; Nakajima, 1986). This implies that the shadow wage rate 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 labour and income space. Household preferences for leisure in income-labour space are formulated as a reservation wage curve that is convex and upward sloping and calibrated to fit the observed seasonal labour supply/leisure demand and wage rates in the area:

$$\begin{aligned} &w_p^* = \beta_1 + \beta_2 D_p + \beta_3(D_p - \beta_4)^2, \\ &D_p = \frac{L_p^*}{W}, \qquad L_p^* \leq \bar{L}_p, \\ &L_p^* = L_{p\rm F} - L_{p\rm H} + L_{p\rm O}, \\ &L_{p\rm F} = L_{p\rm C} + L_{p\rm L}, \qquad L_{p\rm T} = L_p^* + L_{p\rm E} \end{aligned} \quad \text{(A.13)}$$

where βs are parameters, D_p is the seasonal family labour divided by the household labour force (W), $\bar{L}_p$ is the maximum time which is available for work,[12] $L_{p\rm C}$ is seasonal family labour in crop production, $L_{p\rm L}$ is seasonal family labour in livestock production, $L_{p\rm O}$ is seasonal off-farm family labour, L_p^* is total seasonal family labour, $L_{p\rm F}$ is total seasonal on farm labour and $L_{p\rm H}$ is hired labour, $L_{p\rm T}$ is the total seasonal time endowment, and $L_{p\rm E}$ is the seasonal leisure time. Labour for conservation (building of new structures, maintenance of structures, and removal of old structures) is included in $L_{p\rm C}$. The religious holiday constraint may be binding and limit labour supply in some periods of the year. The shadow wage is determined by the intersection of the wage equation with the labour constraint. We have not included a gender division of labour in the model because of the difficulties it would involve. This may imply that labour allocation is more efficient in the model than in reality.

[12] 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.

- *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 the 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 and this land is rented in by households with two or more oxen. The share of the output paid to the owner varies from 0.5 on the best land to 0.25 on poorer land. The scarcity of land in the area in combination with the stickiness of the 'price' in form of share of the output, cause demand (denoted by superscript d) for land to exceed supply (Holden and Shiferaw, 2000). Actual rented land cannot exceed the supply, however. A good reputation is important in order to be able to rent in land. For households renting land, denoted by superscript 2, we get:

$$A^2_{q\mathrm{o}} = \bar{A}^2_{q\mathrm{w}} + A^2_{q\mathrm{r}}, \qquad A^{2\mathrm{d}}_{q\mathrm{r}} > \gamma A^{0\mathrm{s}}_{q\mathrm{r}}|\bar{\alpha}_q,$$
$$A^2_{q\mathrm{r}} \leq \gamma A^{0\mathrm{s}}_{q\mathrm{r}}|\bar{\alpha}_q \qquad \text{(A.14)}$$

where $A^2_{q\mathrm{o}}$ is a vector of operated land holding (subscript o) by land type (subscript q), $\bar{A}_{q\mathrm{w}}$ is a vector of owned land (subscript w) by land quality class, $A^2_{q\mathrm{r}}$ is 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 are equal to 0.5 for the best quality land, 0.33 on medium quality land and 0.25 on poor quality land. With these shares there γ is excess demand. 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:

$$A^0_{q\mathrm{o}} = \bar{A}^0_{q\mathrm{w}} - A^{0s}_{q\mathrm{r}}|\bar{\alpha}_q \qquad \text{(A.15)}$$

- *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 due to moral hazard problems and the risk of their oxen being mismanaged. Oxen may be borrowed or rented, $\mathrm{Ox}_{\mathrm{r}p}$, from relatives or close neighbours, usually in exchange for labour (interlinked markets). Seasonal oxen working days, $\mathrm{Ox}_{\mathrm{o}p}$, is therefore the sum of the working days by owned oxen ($\mathrm{Ox}_{\mathrm{w}p}$) and the amount of oxen days rented in or out ($\mathrm{Ox}_{\mathrm{r}p}$) during the period. Available oxen labour days from own oxen is limited by the number of religious holidays in the month.

$$\mathrm{Ox}_{\mathrm{o}p} = \mathrm{Ox}_{\mathrm{w}p} \pm \mathrm{Ox}_{\mathrm{r}p},$$
$$w_{\mathrm{lo}} L_{\mathrm{lo}p} = \mathrm{Ox}_{\mathrm{r}p} \leq \overline{\mathrm{Ox}}_{\mathrm{r}p},$$
$$\mathrm{Ox}_{\mathrm{w}p} \leq \overline{\mathrm{Ox}}_{\mathrm{w}p} \qquad \text{(A.16)}$$

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

- *Fodder market*: Fodder is supplied by crop stover, grass production on grazing 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:

$$\mathrm{Fo} = \kappa\theta yi_{\mathrm{Cr}A_q} A_{\mathrm{Cr}} + \kappa \mathrm{Fo}^{\mathrm{d}}, \qquad \mathrm{Fo}^{\mathrm{d}} \leq \overline{\mathrm{Fo}} \qquad \text{(A.17)}$$

where $\theta yi_{\mathrm{Cr}A_q}$ is a vector of stover or fodder yields for different crops, including grass and fallow land, for different land types, and κ is a vector of dry matter conversion factors.

- *Seed market*: It is assumed that markets for seed function well but a price band is included making the price of purchased seeds 5% higher than the selling price. Households also have the option of storing seeds from their own harvest for the next season.
- *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% higher than the selling price.

A.2. Land degradation and conservation

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

$$\mathrm{se}_{A_q} = \mathrm{se}(A_q, \psi_{\mathrm{r}}, \mathrm{Cr}, \Psi) \qquad \text{(A.18)}$$

Soil erosion rates were determined based on field experiments carried out by the SCRP in the study area.[13] 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 (soil type depth and land slope). Soil erosion affects soil depth (sd) through a transition equation:

$$\mathrm{sd}_t = \mathrm{sd}_{t-1} - \tau \mathrm{se}_t \qquad \text{(A.19)}$$

where τ is a conversion factor.

Nutrient depletion in the model focuses on nitrogen and phosphorous which are considered to be the main nutrients limiting crop production in the area. The balance or depletion per unit of land at the plot level depends on the land/soil type, the stock of nutrients in the soil, crop choice, conservation technology use, yield, application of fertiliser and manure, and the release of nutrients from the soil. Nutrients are also lost through eroded soil and this soil is richer in nutrients than the soil remaining behind.[14] Release of nitrogen from the soil is assumed to depend on the stock of nitrogen.[15] The change in N stock is given by:

$$\mathrm{N}_{t+1} = \mathrm{N}_t - \varphi(\mathrm{N}_t - \eta(\mathrm{se}_t)) - \eta(\mathrm{se}_t) \qquad \text{(A.20)}$$

where N is nitrogen, φ is the share of nitrogen mineralised in each period and η the nitrogen composition of the soil. The change in plant available N from period to period (ϕ) due to nutrient depletion is computed as:

$$\phi = \varphi(\mathrm{N}_t - \mathrm{N}_{t-1}) \qquad \text{(A.21)}$$

The reduction in plant available nitrogen is included in the production function (Eq. (A.23)). The nutrients in animal manure are released over 2 years with 60% being released in the first year and the rest in the following year. The effects of nitrogen and rooting depth depletion on yields are therefore included while the effect of phosphorus depletion is not included. This is because incorporation of this effect would require additional data on P-fixation, conversion of stabile P to labile P and the total P stock in the soil.

Households may decide to conserve their land by introducing conservation structures (graded soil/stone bunds). Only labour is needed as an input for this, 100–120 working days/ha, depending on the slope of the land. Maintenance of the structures requires an additional 15–20 working days per year and hectare. 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 food-for-work in the early 1980s. Therefore, in our model households may also decide to remove conservation structures and this is estimated to take only 25% of the time required for construction. The conservation structures may occupy some productive land, therefore reducing the effective cropping area and this may reduce initial crop yields. Two formulations of the model are used here, (a) where the yield loss is negligible, and (b) where initial yields are reduced by 5–10% depending on the slope of the land. Building or removing conservation structures may therefore affect long-term as well as short-term yields. The long-term effect goes through the impact on land degradation and the feedback through crop yields.

A.3. Crop production

Yields of different crops are functions of soil type, soil depth, slope, application of fertiliser and manure converted into nitrogen and phosphorus (P), and conservation technology (Ψ). The intercept of the yield ($\mathrm{yi}_{\mathrm{int}}$) function, suppressing the crop type and

[13] It may be questioned whether the erosion experiments captured the inflow of soils and not only the outflow, that is whether there could be soil accumulation somewhere in the watershed. Definitely, conservation structures 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 experiments, conservation technology experiments 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. Spatial externality effects may be underestimated. They may, however, go in both directions (be positive or negative) in terms of how they affect crop yields. They may, e.g. contribute to gully formation and sediment accumulation that negatively affect yields.

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

[15] We assume that 1% of the nitrogen stock is released each year.

year, is a function of soil type (A_q) and soil depth (sd):

$$\mathrm{yi}_{\mathrm{int}} + \mathrm{yi}(A_q, \mathrm{sd}) \quad \text{(A.22)}$$

The impact of soil depth on crop yield intercepts was estimated econometrically using farm level experimental data from the study area and testing alternative functional forms.[16] The final yields, including inputs, were also estimated econometrically;[17]

$$\mathrm{yi}_{A_q} = \mathrm{yi}(\mathrm{yi}_{\mathrm{int}}, \Psi, \mathrm{N_F}, \phi, P_\mathrm{F}) \quad \text{(A.23)}$$

where $\mathrm{N_F}$ is fertiliser and manure nitrogen added, ϕ is the change in available mineralised nitrogen, and P_F is phosphorus added through fertilisers and manure. Yields may be influenced by conservation technologies (Ψ) as conservation structures take up some part of the land, the structures may harbour pests, they may reduce runoff and 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.

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

A.4. 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, ploughing capacity, manure production, culling rates, labour and other input costs are included. For example, cattle are divided in male and female calves, bulls, heifers, cows and oxen. The model is calibrated to the average livestock holdings for the different household groups, to the productivity and lifetime of the local breeds of livestock. The number of animals in each category is therefore a continuous number, not an integer. This applies to rearing, purchase, slaughter and sale of animals. Adult animals kept in a specific period are computed as:

$$\mathrm{LVP}_{t+1} = (1 - \varsigma - m)\mathrm{LVP}_t + \mathrm{LVB}_{t+1} + \mathrm{LVR}_t + \mathrm{LVS}_{t+1} \quad \text{(A.24)}$$

where LVP is animals kept in production, ς 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:

$$b\,\mathrm{LVP}_{\mathrm{f}t} = \mathrm{LVR}_t + \mathrm{LVRC}_t + \mathrm{LVRS}_t \quad \text{(A.25)}$$

where b is the birth rate, $\mathrm{LVP_f}$ 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 spent different age classes and their reproduction characteristics (determined from survey data and literature).

The decision to buy or sell animals depends 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 animals. In order to avoid complete disinvestment in the terminal year, the model is constrained to such that not more than 20% of the stock can be sold in the terminal year.

A.5. 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. On the other hand, crop residues are an important source of animal fodder. Stover yields are modelled to be a function of crop type and crop grain yields. Crop choice, crop management, e.g. use of fertiliser 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:

[16] See Shiferaw and Holden (2001) for details.

[17] Using data from FAO fertiliser demonstration plots for the Debre Berhan area, assessing alternative functional forms.

$$\mathrm{Fo} = \kappa\theta \mathrm{yi}_{\mathrm{Cr}A_q} A_q + \kappa \mathrm{Fo}^{\mathrm{d}} \geq \varpi \mathrm{LVP} \quad (A.26)$$

where ϖ 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:

$$\mathrm{Ma} = \varepsilon \mathrm{LVP} \quad (A.27)$$

where ε is a vector of the farmyard manure production per animal by animal type which is utilised as farmyard manure (excluding the part used for fuel).

The system of free grazing outside the cropping season is not captured in the model. Likewise, the prestige value of animals is not included. There may therefore be more incentives to keep livestock than are captured by the model.

A.6. 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). 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:

$$\begin{aligned} &p_g X_g = \alpha_1 + \alpha_2 E(I) + \alpha_3 E(I)^2, \\ &X_g = \mathrm{XP}_g \mathrm{XB}_g + \mathrm{XS}_g, \\ &X_g \geq X_{g\,\min}, \qquad \mathrm{nu} X_g \geq \mathrm{Nu}_{\min} \end{aligned} \quad (A.28)$$

where p_g is a vector of food prices, X_g a vector of foods consumed, α_1, α_2, α_3 are expenditure system parameters, XP_g is own production 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 two last equations include the additional food preference and minimum energy, fat and protein requirements.

A.7. Full income and cash constraints

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

$$\begin{aligned} E(I) = {} & p_{\mathrm{C}}^{\mathrm{e}} \mathrm{yi}_{\mathrm{Cr}A_q}^{\mathrm{e}} A_q - p_{q\mathrm{C}} Q_{\mathrm{C}} + p_{\mathrm{L}}^{\mathrm{e}} \mathrm{yi}_{\mathrm{L}} \mathrm{LVP} \\ & - p_{q\mathrm{L}} Q_{\mathrm{L}} + w_{po} \mathrm{OF} + w_p^* \mathrm{Le} \end{aligned} \quad (A.29)$$

where $p_{\mathrm{C}}^{\mathrm{e}}$ and $p_{\mathrm{L}}^{\mathrm{e}}$ are vectors of expected prices[18] for crop and livestock production, $p_{q\mathrm{C}}$ and $p_{q\mathrm{L}}$ are prices of inputs in crop and livestock production, Q_{C} and Q_{L} are vectors of non-labour 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 labour market.

The cash constraint for farm input purchase is derived from the extended quadratic expenditure system. The quadratic term was insignificant and was therefore omitted.

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