Poverty and natural resource management in the Central Highlands of Eritrea

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Chapter 7

Estimating Model Parameters

7.1 Introduction

Before analysing land use and land management decisions of farmers in the Central Highlands of Eritrea, we first discuss the estimation of parameters of the dynamic mathematical model discussed in the previous chapter. The parameters include availability of land and labour; labour and other inputs required in different periods of the year; crop and biomass yields for various land categories and technologies; livestock characteristics; consumption patterns in rural areas and various prices. Estimation of these parameters is based on both primary and secondary data. Primary data we gathered during the field research is discussed in Chapter five. Secondary data come from many resources such as published and unpublished reports of various ministries and research stations in Eritrea, relevant literature from neighbouring countries and regions with similar characteristics as well as data generated by making use of simulation models developed in international research institutions (Hengsdijk, 2003).

7.2 Land

Classification of land into different land categories was done by land use experts from the Eritrean Ministry of Land Water and Environment. The land classification system used by the above mentioned land use experts is based on a widely used system of land evaluation developed by the United States Department of Agriculture. The classification is mainly based on soil depth and slope and indicates the extent of physical limitations of a given land to crop growth. According to this system land is classified into eight groups. For the purpose of our analysis, however, the number of land categories is reduced to four groups. The slope and soil depth range of each land category is given in Table 7.1, which also shows the size of land under each land category in the study villages[25].

[25] Soil depth varies with a given slope as well. However such detailed classification of land types was not possible. Thus the land classification is basically done based on slope and the average soil depth for each slope category was determined.

Table 7.1 Total land areas in these study villages by land type

Land Categories	Slope	Soil depth (cm)	Area of Land (ha)		
			Embaderho	Maiaha	Zibanuna
S1	0 - 8 %	> 100	88.87		604.06
S2	8 – 16 %	25-50	511.59	68.13	109.23
S3	16 – 30 %	< 25	1690.51	225.82	62.35
S4	> 30 %	< 25	20.74	727.77	0.00
Residential			67.95	16.22	42.80
Dams			23.40	0.00	10.84
Total Area			2403.06	1037.94	829.28

Source: Field measurements by MWLE staff (2002).

At present there are almost no native woodlands in Embaderho and Zibanuna and no eucalyptus plantations in Maiaha. The total area of plantations in Embaderho and Zibanuna are 46.9 ha and 21.5 ha respectively. Acacia woodlands in Maiaha were estimated to cover 50 percent of the total land.

7.3 Labour supply and requirement

In this section we discuss how the parameters relating to the availability of labour and labour requirements for crop, livestock and other activities were obtained.

7.3.1 Labour supply

The total number of people in the study villages, the age and gender composition, number of religious holidays in which agricultural activities could not be done and the length of the period under consideration determine the availability of labour in each period.

Population size and composition

The total number of people and household composition of the three subregions of the Central Highlands of Eritrea are presented in Table 5.2. The total population in the three study villages, Embaderho, Maiaha, and Zibanuna is also reported in Section 5.3.2. On the basis of the age and gender composition presented in Chapter five, we derive the total number of working people, number of adult persons and adult male persons for the above three villages.

The demographic characteristics of the three study villages are similar. It has been described in Chapter five that, on average, about 29 percent of the population are children below 10 years of age and 4.7 percent are older than 75.

Thus total number of working persons is about 66 percent of the total population. Adults refer to people between the ages of 18 and 75 and this is 38 percent of the population. Both household size and family composition vary considerably for the male-headed and female-headed households. To estimate the number of adult male labour we first distinguish between male and female-headed households. Male-headed households constitute 70 percent of the households (Table 5.5). These households are composed of 50 percent males and 50 percent females. Female-headed households constitute 30 percent of the households and are characterised by lower family size and lower number of adult males. We assume that 20 percent of the persons in a female-headed household are males.

Thus the proportion of adult male population in a village will be (0.7 * 0.5 * 0.38) for the male-headed households plus (0.2 * 0.30 * 0.38) for female-headed households. This results in 0.156 (15.6%) adult males in the population. The total number of people, number of working persons, number of adult persons and number of adult male persons in Embaderho, Maiaha and Zibanuna are presented in Table 7.2

Table 7.2 Labour availability

Village	Number of People (a)	Number working persons[1] (b)=(0.66*a)	Number of adult persons (c)=(0.38*a)[2]	Number of adult male persons D=(0.155*a)	Working time: fraction of available time (%)
Embaderho	5600	3696	2128	872	0.48
Maiaha	654	432	249	102	
Zibanuna	1480	977	562	229	

1 people between the age of 10 and 75 years old
2. people with the age of 18 and 75 years of old
Source: Based on own field survey (2002).

Religious holidays and labour availability

The total amount of labour available in each period has to be adjusted for the number of days in each period as well as for the number of days households are not allowed to undertake agricultural activities due to religious holidays. The total number of days in a given period will be 15 or 30 days (see 6.2). As discussed in Chapter five (Section 5.4), most agricultural activities such as ploughing, weeding, harvesting and threshing cannot be done during religious holidays. The religious holidays include all weekends and at least 10 other days dedicated for saints every month. But there may be overlapping between these days and the weekends. The number of days that overlap with the weekends range from one to four depending on the day the month starts and is on the average 2.86. The average number of weekend days in a month of 30 days will be 8.57 = (8/28 * 30). The number of days dedicated for saints in each month will be 7.14 = (10 – 2.86). Thus only 48 percent of the total days in each period will be available for agricultural activities[26].

7.3.2 Labour requirements

Labour requirement for cropping activities

Labour required for various agricultural activities varies considerably between the wet and dry season. The average labour requirement for the major agricultural activities in the study villages is discussed in Chapter five (see Table 5.8). The crop calendar, which describes the periods during which each activity should be carried out, is also presented in figure 5.1. The total labour requirement for undertaking the major agricultural activities in each period is calculated based on the above information. Oxen requirements are related to the various agricultural activities. The current crop production system indicates that two oxen days are required for every manday involved in ploughing or threshing.

Labour requirements for the application of manure, and stone bunds were not estimated from the survey. We describe the procedure we followed to arrive at estimates in the following sections.

Labour requirement for stone bunds

The amount of labour required for constructing stone bunds per unit area depends on the distance between bunds, which in turn, depends on the slope of the land. Assuming a one meter vertical interval[27], the length of stone bunds (km/ha) and the total number of mandays required per ha of land for the different land categories are presented in Table 7.3. The work norm for forestry activities from the Department of Land and Crop Production in the Ministry of Agriculture indicates that the construction of stone bunds require 125 mandays/km plus 20 mandays/km for maintenance (MOA, 2001).

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[26] This is in fact a conservative estimate because a number of holidays that are observed annually are not included. Also, while some more holidays are observed in each locality, only holidays universally observed in the Highlands are included.

[27] Hurni (1985) suggests that a vertical interval of twice the depth of a workable soil. As the soils in the Highlands of Eritrea are very shallow, however, this leads to spacing that is too narrow to be practicable.

Table 7.3 Labour requirement for constructing stone bunds on different land categories

Slope category (%)	Mean slope (%)	Distance between bunds (m)	Length of structure (km/ha	Labour input mday/ha
0-8	4	25.0	0.4	50.0
8-16	12	8.3	1.2	174.0
16-30	23	4.3	2.3	333.5
> 30	37.5	2.7	3.8	543.8

Source: Based on MOA (2001).

Labour requirement for transportation

The number of man and animal days required to transport crops, crop residues and manure depends on distance of croplands from the homestead and on the means of transport. Most of transport activities are done by donkeys. Following Hengsdijk *et al.* (1996), we assume a 100 kg capacity per trip and four trips per day.[28] This results in a maximum daily transport capacity of 400 kg per donkey per day. The transport will also involve one person. Thus 0.25 mandays and 0.25 donkey-days are required to transport of 100 kg of crops, crop residues or manure.

Labour requirement for livestock activities

Labour requirements for livestock activities depend to a large extent on the size of herd, production situation (restricted or open grazing), as well as grazing systems practised, i.e., the distance to the pasture and seasonal migration. Rural households in most of the villages in the Central Highlands form groups and keep their livestock in rotations. Observations during the fieldwork show that one person keeps up to 50 sheep/goat or 25 cattle. This is equivalent to 0.02 persons/day/animal for sheep and goats and 0.04 persons/day/animal for cattle. We will also use 0.02 persons/day/animal for donkeys.

Labour requirement for tree planting

According to the work norm for forestry activities of the Department of Land and Crop Production in the Ministry of Agriculture, the activities required and number of mandays needed to undertake various activities related to tree planting are seedling production: 30 seedlings per manday, preparing pits: 25 pits per manday, and planting: 70 plants per manday. It is also the norm of the department to plant 2000 seedlings per ha which results in labour requirements of 66.67, 80.00 and 28.57 mandays per ha for seedling production, pitting and planting respectively. The above activities are not required for acacia woodlands, which are assumed to regenerate naturally.

[28] This is based on an average speed of 4 km per hour, 6 working hours per day and an average village-field distance of 3 km.

Labour requirements for cutting of trees is assumed to be 500 mandays/ha and 200 mandays/ha for eucalyptus plantations and natural woodlands respectively. Both the density and size of trees in plantations is often larger in Eucalyptus plantations than on acacia woodlands.

7.4 Crop yields and agricultural technologies

Understanding the relationship between inputs and outputs of different agricultural activities is crucial in analysing the economic and environmental impacts of new technologies and policy instruments. Agricultural activities result in desirable outputs such as grain yields and crop residues and undesirable outputs such as soil erosion or nutrient depletion (van Ittersum and Rabbinge, 1997). As we have seen in the previous chapters, the interactions between socio-economic and biophysical conditions are complex and the analysis requires both socio-economic data such as resource endowments, prices and infrastructure as well as biophysical data that determine the actual and potential production activities. Quantitative analysis is needed to disentangle the complex relationships involved. Thus, technical options for crop and livestock production have to be defined in terms of input-output coefficients (Hengsdijk and van Ittersum, 2002). For example, coefficients that relate technical options such as stone bund, mulching and fertilizer on the one hand and outputs such grain yield, soil loss and nutrient balance on the other are required to analyse the economic and environmental impacts of each option.

For production activities and technologies applied in practice, coefficients that relate inputs to some outputs (e.g. crop yield) can be derived from econometric analysis of empirical data collected using field surveys. Input-output coefficients for alternative technologies, and coefficients that relate inputs to outputs that cannot be easily measured in field surveys (e.g. nutrient balance), on the other hand, can be derived only from field experiments or agro-ecological simulation procedures. There are very few experimental results in Eritrea that can provide us with data required for this study.

This section discusses how the input-output coefficients required in this study are derived. Most data relating to crop and livestock activities are based on a Technical Coefficient Generator (TCG) developed for the highlands of Northern Ethiopia (Hengsdijk, 2003). Empirical data relating to Eritrea are analysed and presented in Section 7.9 for purposes of comparison and to obtain additional data. We first provide a description of the TCG.

7.4.1 The Technical Coefficient Generator

The TCG is a model that enables to structure basic knowledge and data in order to quantify the inputs and outputs of alternative land use systems (Ruben *et al.,* 2003; Hengsdijk, 2003). The TCGs generally use a 'target-oriented' approach for quantification of inputs and outputs. That is, TCGs determine the technically optimal combination of inputs required to achieve a predetermined production level (target output). These predetermined production levels vary from maximum yields, which is the potential yield for given climate, soil and crop characteristics, down to very low yield levels.

Potential yields are first estimated, using a crop growth simulation model for given climatic conditions, while other conditions such as nutrient availability and land management being optimal. The WOFOST model, which is a quantitative model that simulates growth in time and production of annual crops based on various sets of crop parameters, soil characteristics and daily meteorological data, is used to estimate the potential yields for the TCG.

In order to estimate potential yields in a given physical environment and actual yield levels under various constraints, the TCG uses the concept of hierarchical yield levels. Actual yield levels are classified as a function of different production factors i.e., growth-defining (e.g. temperature), growth-limiting (water or nutrients) and growth-reducing (e.g. pests or weeds) (Hengsdijk and van Ittersum, 2002). The structure of the TCG developed for northern Ethiopia (TCG-Tigray) and the calculation rules applied are largely based on TCGs earlier developed for Mali and Costa Rica (Hengsdijk *et al.,* 1996; 1998). We will describe the main features the TCG-Tigray and the type of data it generates.

The design of TCGs, i.e., the choice of activities and technologies to be included, depends on the characteristics of the physical environment as well as socio-economic and environmental objectives. Choice must be made between the large number of activities (e.g., types of crops included) and various production techniques to be included. Depending on whether the objectives have a socio-economic character, or environmental one such as reducing soil erosion, alternative management criteria that refer to the ratio between labour and capital, or soil conservation techniques resulting in different levels of soil loss need to be included. Table 7.4 provides the definition criteria of various crop systems in TCG-Tigray and the variants included in rain-fed cropping system.

Table 7.4 Design criteria for various cropping options in TCG

Attribute	Design criteria	Number of variants
Physical environment	Zone	Two different zones can be selected, with different soil types and climate
	Type of rainfall year	Three years for the first zone and Sixteen years for the second zone can be selected representing different levels of rainfall
	Soil type	Eleven soil types based on slope, soil depth and presence of stones: six for the first zone and five for the second zone
Plant type	Crop types	Five crops: Sorghum, wheat, barley, pulses and millet
	Production level	Nine yield levels: potential yield is reduced stepwise with 10% until a minimum of 20% of the potential yield
Production techniques	Sowing dates	Twelve separate sowing dates can be selected
	Mechanization level	Two levels of mechanization: low, manual field operation and high, animal traction
	Crop residue strategy	Three strategies: field grazing and burning of residues, mulching, and harvesting residue for feeding cattle
	Weed Control	Two strategies: manual weeding and use of herbicides
	Pest and disease control	Two strategies: no biocides and use of biocides
	Soil conservation measures	Two strategies: no bunds and stone bunds

Source: Based on Hengsdijk (2003)

As the soil types in the TCG-Tigray did not fit the land classification in this study and because we wanted to use the model to generate data for three villages with different altitude and rainfall levels, it was necessary to make some adjustments. Thus, new levels of potential yields were generated using WOFOST for land types s_1 to s_4 (see Table 7.1) and for each study village.[29] In addition, higher level of rainfall is selected in generating the data for Zibanuna compared to the rainfall levels used in the cases of Embaderho and Maiaha.

[29] Note that WOFOST is not an integral part of the TCG. Only potential yields determined by WOFOST simulations are included in the TCG.

The options considered in this study include four soil types[30], one mechanization level (animal traction), two crop residue strategies (mulching and harvesting residues), one weed control method (manual weeding), no use of biocides and two conservation methods (stone bund and no stone bund). Nine different levels of target output were also set, ranging from 20 percent to 100 percent of the water-limited yield level and the inputs (N, P, and K) required to achieve each target yield under various crop residue strategies and soil conservation methods were generated by the TCG. This way the inputs and outputs for different combinations of land management and soil types were generated for the major crops in the Central Highlands of Eritrea: barley, wheat, sorghum, millet and beans[31]. In total, 144 different combinations of inputs and outputs were obtained for each crop. The inputs used in the analysis include nutrients N, P, K, quantity of biomass used as mulch, and stone bunds. The outputs on the other hand include desirable output such as grain and crop residues and undesirable ones such as soil erosion and nutrient losses.

While the TCG-Tigray generates crop yields, crop residues and soil loss, it does not generate nutrient losses. The procedure in the TCG, as previously stated, is a target-oriented approach and can be described as follows: First nutrient outflows from the system due to various reasons (erosion, leaching, volatilization) and nutrient inflows from natural sources (such as atmospheric deposition and N - fixation) are estimated. Then for each level of target yield, nutrients that will be taken up by crops and crop residues are estimated and nutrient inputs requirement that will make up for the differences between total nutrient inflows and outflows are determined. The implication in the above procedure is that in/outputs of nutrients are always in balance. Also if there are no nutrients there will be no or too little yield. However, the actual practice in the Highlands of Eritrea is that farmers generally apply little or no fertilizer, which implies a decline in the stock of nutrient in the land (soil mining).

To arrive at reasonable estimates of yields for different levels of fertilizer application, and to be able to estimate changes in nutrient balance on croplands, it is necessary to take into account the uptake of nutrients by crops from the pool of nitrogen in the soil. This will be discussed in Section 7.5.2. In the next section we present a statistical estimation of yield functions based on the data generated using the TCG.

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[30] Detailed soil characteristics required by the TCG were not possible to obtain for the study villages.
[31] Taff is not included in the TCG. The coefficients for taff are assumed to be the same as for barley.

7.4.2 A statistical analysis of results from TCG

Ruben and Ruijven (2001) point to limitations of simulation models and suggest Meta modelling techniques as supplementary tool. A Meta model is an approximation of the input/output transformation that is implied by the simulation model (Kleijnen 1997, p.2). A meta model may be developed for various reasons: 1) meta modelling simplifies the outcomes of simulation models, with the objective of gaining insight into the critical relationships within the simulation procedures, 2) meta models are often much smaller in size and can be used to replace the original simulation model in subsequent analysis, and 3) meta models are used for the validation and verification of the robustness of the simulation models. The first two are the main reasons for using a Meta modelling technique (from TCG simulation model of Hengsdijk, 2003) in this study.

The large number of data points generated by the TCG was statistically analysed to derive continuous functions. A Cobb-Douglas production function was fitted for each crop separately[32] as follows.

$$\ln Y = \beta_0 + \beta_1 \ln(N) + \beta_2 \ln(P) + \beta_3 \ln(K) + \beta_4 Mulch + \beta_5 Bund + \beta_6 STYPE2 + \beta_7 STYPE3 + \beta_8 STYPE4 \qquad (1)$$

Where Y represents crop yield in kg/ha, N, P, and K, quantities of nitrogen, phosphorus and potassium in kg/ha respectively, Mulch refers to the quantity of crop residue used as mulch in kg/ha, Bund is a dummy variable equal to zero for no bund and 1 for stone bund. STYPE2, STYPE3 and STYPE4 are dummy variables, which are equal to 1 if land is of soil type s2, s3 and s4 respectively, and equal to 0 otherwise. The expected sign for the coefficients of all variables are positive except for s_2, s_3 and s_4, which are negative. The results for Embaderho village are presented in Table 7.5.[33]

The variable K in all cases had either the wrong sign or was not significant. This is probably due to the very high levels of correlation between N and K[34]. Thus the variable K was dropped from the regression. STYPE2 was not significant in the case of barely, pulses and wheat. All the remaining variables have the expected sign and are highly significant. N and P are expressed in logarithms and therefore the coefficients are elasticities. For example a one percentage change in the quantity of nitrogen applied to barley results in about 0.41 percentage change in the yield of barley. In the case of mulching, as both the options with and without the application of mulch are considered, half of the observations had zero values. Thus we did not use the logarithm form. The

[32] The Cobb-Douglas production function is used because it resulted in the best fit.
[33] The results for the Maiaha and Zibanuna are presented in Appendix 3
[34] The correlation coefficient between and N and K is 0.56.

coefficients of mulching show a percentage change in crop yield for a unit increase in the amount of crop residues applied as mulch. The coefficients of bund show the percentage increase in crop yield due to the application of stone bund. Similarly the coefficients for STYPE2, STYPE3 and STYPE4 show by what percentage crop yields from soil types s_2, s_3 and s_4 are lower than the yield of crop from soil type s_1. Adjusted R^2 is 0.94 or above for all the crops. And the D-W test is reasonable with values between 1.4 and 2.6 for all the crops.

7.5 Sustainability indicators

Soil loss and nitrogen balance are the indicators of sustainability used in this study. The relationship between land types and various land management practices on the one hand, and soil loss from croplands on the other is discussed in the following sub-section. A more detailed discussion of soil erosion including some empirical evidences from research stations in Eritrea is presented in Section 7.9. Nutrient balance is discussed in Section 7.5.2.

7.5.1 Soil erosion

Soil erosion is a complex process in which various climatic, topographic and land use and land management factors determine the rate of erosion (see Section 7.9.2). We will use the data generated by the TCG-Tigray to estimate the rates of erosion from croplands under different land management practices. As with yields, soil loss is modelled as a function of nitrogen and phosphorus application, application of mulch, application of stone bunds and soil types. Soil erosion is expected to decrease with the application of NPK, stone bunds and mulch and increase with slope of land. Thus, the coefficients of STYPE2, STYPE3 and STYPE4 are expected to be positive and the coefficients of the remaining variables are expected to be negative. The results are presented in Table 7.6.

Table 7.5 Cobb-Douglas yield functions (coefficients and t-statistics using Ordinary Least Square regression)

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	5.0476***	38.7	4.5436***	18.48	5.3168***	90.67	4.9115***	39.29	4.5563***	42.02
ln (N)	0.4077***	5.88	0.4315***	4.00	0.1933***	7.68	0.5547***	11.12	0.6093***	12.02
ln (P)	0.2759***	4.96	0.0856*	2.0317	0.2933***	14.20	0.1427***	5.03	0.1048***	2.77
Mulch	0.0001***	15.19	0.0002***	9.79	0.0008***	11.14	0.001***	18.35	0.0001***	14.19
Bund	0.0851***	5.52	0.3599***	9.74	0.2211***	5.92	0.0891***	5.32	0.1181***	5.90
STYPE2	-0.0045	-0.34	-0.1544***	-3.76	0.0747	1.29	-0.0932***	-4.10	-0.0162	-0.93
STYPE3	-0.1948***	-8.08	-1.0615***	-11.74	-0.4928***	-9.71	-0.3579***	-11.81	-0.2857***	-12.59
STYPE4	-0.5244***	-10.1	-1.9674***	-9.46	-1.0370***	-14.65	-0.6612	-14.56	-0.7736***	-17.57
No. observ.	144		144		144		144		144	
Adj. R^2	0.98		0.94		0.94		0.96		0.97	
D-W stat	1.56		2.54		1.78		1.62		1.41	

The dependent variable is log(yield). The first three variables are also in logarithm.

D-W Stat is the Durbin-Watson Statistics

* $P < 0.05$

** $P < 0.01$

*** $P < 0.001$

Table 7.6 Soil loss functions (coefficients and t-statistics using Ordinary Least Square regression)

	Barley		Millet		Beans		Sorghum		Wheat	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
C	3.1458***	42.27	2.8158***	32.93	2.5344***	84.64	2.9886***	22.27	3.2328***	51.70
ln(N)	-0.2207***	-6.48	-0.2498***	-6.79	-0.0561***	-5.29	-0.3583***	-6.1643	-0.2764***	-11.07
ln(P)	-0.0472	-1.90	-0.0070	-0.53	-0.0818***	-9.61	-0.0315	-0.7834	-0.0199	-1.20
Mulch	-0.0003***	-46.64	-0.0003***	-29.66	-0.0004***	-13.06	-0.0003***	-42.98	-0.0003***	-63.22
Bund	-0.6759***	-56.96	-0.6169***	-42.62	-0.6926***	-44.94	-0.6560***	-50.78	-0.6763***	-56.18
STYPE2	0.6086***	36.39	0.6324***	39.18	0.5873***	24.58	0.6445***	30.84	0.6126***	36.28
STYPE3	1.4744***	72.74	1.4905***	42.27	1.4996***	60.09	1.5380***	43.15	1.4839***	77.46
STYPE4	1.6275***	0.52	1.7351***	30.93	1.6290***	51.51	1.7626***	30.38	1.6736***	65.99
No. observ.	144		144		144		144		144	
Adj. R^2	0.99		0.99		0.99		0.99		0.99	
D-W stat	3.29		2.95		1.67		2.50		3.20	

The dependent variable is log (yield). The first three variables are also in logarithm.

D-W Stat is the Durbin-Watson Statistics

* P < 0.05

** P < 0.01

*** P < 0.001

All variables except P-fertilizer are significant for all crops at the 1% level. P-fertilizer is not significant in all cases except pulses.

7.5.2 Nitrogen balance

Nitrogen is present in the soil in different forms and various complex processes are involved that affect nitrogen balance overtime and uptake by crops at any given time. A summary model has been developed by Wolf *et al.* (1989) that describes the main processes and which could be used to predict long-term changes in nitrogen balance and plant available nitrogen.

The model distinguishes two pools of soil organic nitrogen – labile organic nitrogen (LON) and stable organic nitrogen (SON) - and four external sources of nitrogen: rainfall (NRAIN), biological fixation (NFIX), inorganic fertilizer (NFERT) and organic materials such as crop residue and animal manure (NORG). Nitrogen from external sources may be transferred to crops, to labile or stable pool, and/or lost in agricultural systems. Nitrogen from the labile pool may be transferred to crop, stable pool or lost to agricultural systems. Nitrogen from the stable pool can only be transferred to the labile pool. Fig 7.1 shows the structure of the model. For a detailed description of the model and the processes involved see Wolf *et al.* (1989).

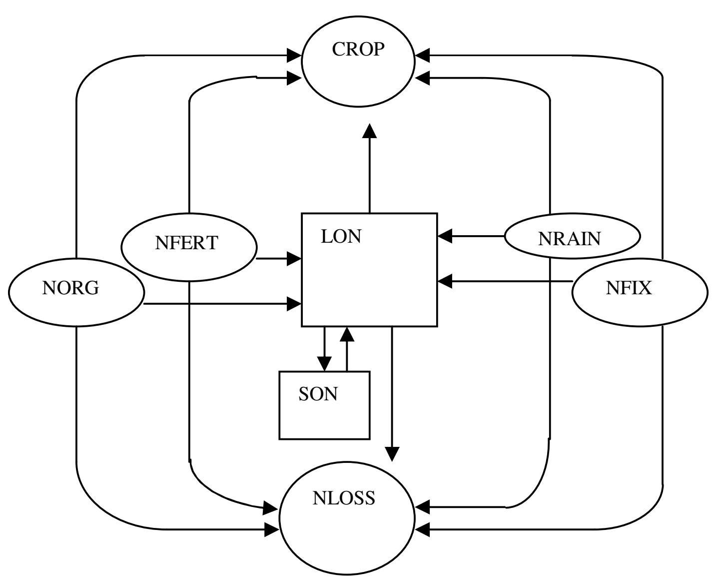


Figure 7.1 Model structure, with in the centre a labile and stable organic nitrogen pool. Nitrogen inputs from biological fixation (NFIX), fertilizer (NFERT), organic matter applications (NORG), rainfall (NRAIN), and from mineralization of LON are partitioned over crop uptake (NCROP), incorporation in the labile pool, and losses (NLOSS).
Source: Wolf *et al.* (1989)

Hengsdijk and van Ittersum (2003) have applied the model for semi-arid conditions in West Africa and tested it with a long-term data set from Saria in Burkina Faso. The model has also been applied to the Koutiala region in Mali and to Tigray region of the Highlands of Ethiopia (Hengsdijk and van Ittersum, 2003; Hengsdijk 2003). Estimations of transfer coefficients of nitrogen originated from different sources to crop uptake, incorporation to the labile pool and losses were obtained from literature and expert knowledge[35]. Table 7.7 shows the transfer coefficients, estimated levels of stable and labile pool of nitrogen, as well as estimated quantities of nitrogen from rainfall and biological fixation used in the TCG-Tigray.

Table 7.7 Annual N inputs via rain (NRAIN) and biological fixation (NFIX), and the fractions transferred to crop, labile and stable pool, and lost N via inorganic fertilizer (NFERT), organic material (NORG), biological fixation, rain and mineralized soil organic matter (LON).

	Transfer coefficients				Source of Nitrogen (kg/ha/year)			
	Crop	Loss	Labile pool	Stable pool	NRAIN (kg/mm)	NFIX (kg/ha)	Labile pool (kg/ha)	Stable pool (kg/ha)
NFERT	0.40	0.40	0.20		0.00065	2.5	222	665
NORG								
Manure	0.30	0.3	0.40					
Crop residues	0.10	0.1	0.80					
NFIX	0.15	0.15	0.70					
NRAIN	0.40	0.40	0.20					
LON	0.425	0.425	0.00	0.15				
SON	0.00	0.00	1.00					

Source: Hengsdijk and van Ittersum (2003); Hengsdijk (2003).

While all nitrogen applied from external sources (NFERT, NORG, NFIX and NRAIN) are transferred to either crop, losses and to the labile pool in the same year, only part of the nitrogen in the labile and stable pools is transferred in any given year. About 1.07 percent of the stable pool is converted every year into a labile pool. Similarly 21.46 percent of the nitrogen in the labile pool is transferred to crop, the stable pool or lost to the system. The initial sizes of the labile and stable pools are set to 222 kg/ha and 667 kg/ha respectively (Hengsdijk, 2003).

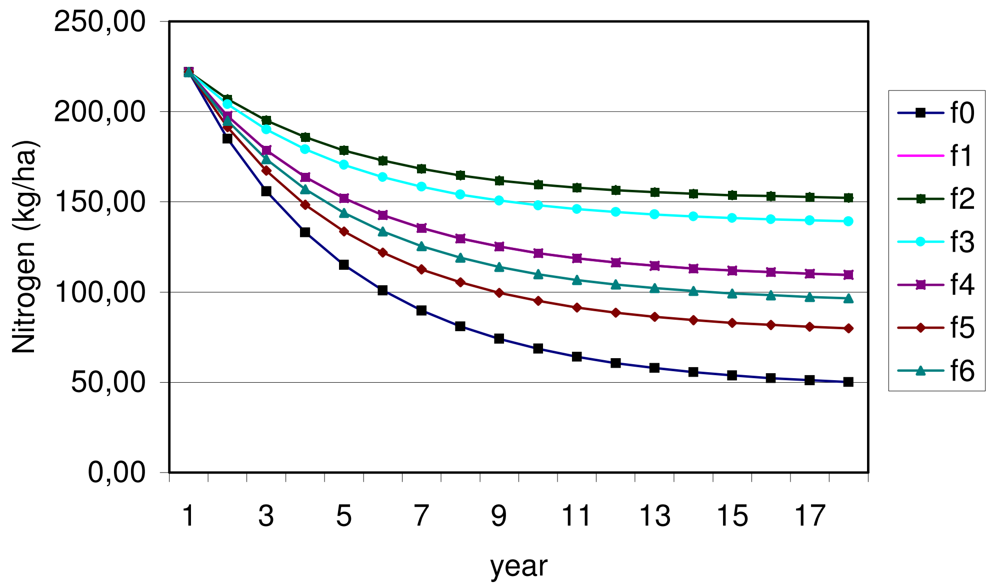
As mentioned in Section 7.4.1, the nutrient-yield relationship implied by the TCG-Tigray reflects a sustainable system in which nutrient inflows and outflows are in balance. The above discussion enables us to simulate the actual (unsustainable system) in the study area. By allowing crops to use nutrients from the pool of nitrogen in the soil, and using the yield function we have already

[35] For a detailed explanation of the estimation of these factors see Hengsdijk and van Ittersum (2003) and Wolf and van Keulen (1989).

estimated, we can arrive at the simulated actual yields. At the same time using the initial pool of nitrogen and the transfer coefficients described above, we can calculate nutrient dynamics in the soil over time.

The amount of nitrogen in the soil declines as part of it mineralises and is transferred to crops or lost due to erosion and other processes[36]. On the other hand, the nitrogen in the soil increases due to supply from external sources. The transfer coefficients for the various types of fertilizers, and hence their contribution to nitrogen balance are different (Table 7.7). As the type and quantity of nitrogen applied to a given plot varies from one year to the other, the calculation of nitrogen balance is very difficult. Thus we estimate the average annual rate of change in the nitrogen in the soil when different types and quantities of fertilizer are applied. Figure 7.2 shows the rate at which nitrogen in the labile pool declines when a certain type of fertilizer is applied.

Figure 7.2 Changes in soil nitrogen for different levels of fertilizer application[37]



[36] Nitrogen inputs from different sources are based on parameters in Table 7.7 and Table A6 (see appendix). Nitrogen loss from the soil due to crop and residue harvests is based on crop yields and parameters in Table A6.
[37] Note: f0 = no fertilizer, f1 = 1800 kg of manure, f2 = 3600 kg of manure f3 = 1800 manure + 500 kg or crop residue, f4 = 50kg Urea + 50kg DAP + 500 kg of crop residue, f5 = 50kg Urea + 50kg DAP, f6 = 100kg Urea + 50kg DAP

As shown in Figure 7.2, the application of organic fertilizers considerably reduces the depletion of nitrogen from the soil. Thus while at the fertilizer application rates considered in this study nitrogen in soil will decline, the rates of decline vary considerably when different types of fertilizer are applied.

7.6 Inputs and outputs of livestock activities

In this section we will discuss feed requirement as well as the outputs of the various types of livestock in the Highlands of Eritrea. No empirical data was available on livestock productivity and feed requirements in Eritrea. However, some values are obtained from the report of National Livestock Development Project FAO (2001), which was based on expert estimations and data from similar environments.

The TCG also provides information on livestock inputs and outputs. The simulation model is based on a stationary herd assumption in which an equilibrium livestock system is described, i.e. a system in which the inputs and outputs are identical each year. Both the herd structure (age and sex composition) as well as the selling strategy of the farmers is specified in such a way that the size and composition of the herd remains the same through time. The model generates feed requirement, milk production and live weight increase for sheep, goat, and cattle.

Live weight gain

As farmers in rural Eritrea sell live animals and not meat, we use the live weight gain to estimate the annual rate of growth in the various types of livestock or the off take rate which is the maximum level of extraction at which the population of livestock can be maintained. If we assume the weight composition of the livestock remains the same, then a live weight gain of the total herd of animals will be due to an increase in their number. Column 2 in Table 7.8 shows the average weight of the herd of different types of livestock, which includes adult animals as well as young ones. Column 3 shows live weight increase per TLU of each type of livestock. The figures in brackets are percentage increase in the number of animals, which are calculated by dividing the live weight increase by 250 (which is the average weight of one TLU) and multiplying by 100[38].

[38] The weight of the additional livestock produced will also be the same as the average weight. Thus the market price of each type of livestock (which often reflects the price of adult animal) will be adjusted to reflect the lower average weight.

Table 7.8 Feed requirement, milk production and live weight gain of livestock

Type of animal	Average weight (kg/animal)	Live weight gain* kg/TLU/yr	Milk Production** litres/TLU/yr	DOM Requirements** kg/TLU/yr
Goats	18.3	79.8 (31.9%)	77.7 (5.7)	1896.0 (138.8)
Sheep	21.1	68.7 (27.5%)	78.0 (6.6)	1960.6 (165.5)
Cattle	180.0	54.3 (21.6%)	125.3 (90.2)	1101.4 (793.0)
Oxen	300.0	-	-	1197.2 (1436.4)

* Figures in bracket refer to annual rate of increase in the number of livestock
** Figures in brackets refer to milk production or feed requirement per animal per year. This is based on TLU = 250 kg animal and the average weight of each type of livestock shown in column 2 of Table 7.8.
Source: Based on Hengsdijk (2003).

The estimated rates of growth for goats and sheep (31.9 and 27.5 percent respectively) seem to be reasonable compared to the FAO estimation for Eritrea of 30% and 25% percent off-take rate for goats and sheep respectively (FAO, 2001). The study maintains that a significant proportion of the goats deliver twins or triplets that the off-take rate should be a minimum of 30 percent. The 21.6% rate of growth of cattle however is extremely high when compared to the FAO (2001) estimate of 9%. Such a very low off-take rate is because the FAO estimate is based on a 20% cows in the herd composition due to the high proportion of oxen in the highlands. In our analysis however, oxen are considered as separate type of livestock and the number of male animals in the cattle are just sufficient of reproduction purposes. Thus if we assume the proportion of cows is 80 percent of the herd, then off-take rate will be much higher.

Milk production

The production of milk from goats, sheep and cattle is 5.7, 6.6 and 90.2 litres per animal per year respectively. This is considerably higher than the FAO estimates, which are 2.5 and 30 litres per annum for goats and cattle respectively. For cattle, as discussed above, this can be due to the low number of cows in the herd. If we assume cows make up 60 percent of the herd, the average annual production of milk will be 90 litres per animal, which is similar to Hengsdijk's estimate. Similarly, the FAO study assumes that milking goats constitute only 10 percent of the herd, which seems to be very low. For sheep and goats we will take an annual milk production of 6.1 litres per animal per year, which is the average of the two estimates.

Feed requirement

Maintenance energy requirement relative to live weight is higher for small compared to large ruminants. Results from Hengsdijk's agro-ecological simulation model are presented in Table 7.8. The DOM requirement per kg of live weight for sheep/goats is considerably higher than the requirement for cattle. The figures in brackets, in column 5 are feed requirement per animal per year. These are calculated for each type of animal by dividing the DOM requirement per TLU by 250 and multiplying by the weight of the respective livestock type. The above estimates are slightly higher than the DOM requirement per animal for all types of livestock estimated by FAO, which may partly explain the higher yields of milk and off-take rates[39].

7.7 Grass and wood production

7.7.1 Grass production

Rangelands in Eritrea provide most of the feed for livestock. Most of the rangeland in the country is classified as open savannah with the botanical composition reflecting both rainfall and the extent of past utilization. The situation of pasture in the Central Highlands is extremely poor mostly because, due to the declining crop yields and increasing population, livestock are pushed to less fertile steep hillsides with low potential for grazing. The annual yield of grass is influenced by rainfall and soil quality. The Agricultural Sector Review estimates the production of feed from fertile and infertile soils under different rainfall regimes as follows (FAO 1997).

Table 7.9 Model sustainable rangeland utilization.

Rainfall (mm)	DM Yield (kg/ha)		Available Feed (kg/ha)*		Stoking Rate (ha/TLU)**	
	Fertile	Infertile	Fertile	Infertile	Fertile	Infertile
200	600	300	400	100	18.6	74.0
400	1200	600	1000	400	7.4	18.6
600	1800	900	1600	700	4.7	10.6
800	2400	1200	2200	1000	3.4	7.4

TLU 250 kg live weight
DM dry matter content of forage
* Ideal minimum residue for ground cover 200 kg/ha
** Based on maintenance diet 6.2 kg DM/TLU/day = 2.232kg TLU/year and 30% utilization level

Source: FAO (1997).

We will assume that fertile soils refer to soil type s_1 and infertile to soil type s_4 in our model. We will also assume that yield declines linearly from s_1 to s_4. Thus for an average rainfall of 500 mm/year, the DM yield for s_1, s_2, s_3 and s_4 will be 1500, 1250, 1000 and 750 kg/ha respectively[40]. For the West African savannah the following equation is suggested.

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[39] FAO (2001) estimate of DOM requirement are 104.1, 104.2, 740.8 and 834.5 kg/animal per year for goats, sheep, cattle and donkeys respectively.
[40] For the West Africa savannah the follow.

$$\text{Biomass Production} = 0.15 + 0.00375R,$$

Where R is rainfall in mm

For an average annual rainfall of 500 mm, this results in a yield (2025 kg/ha/year) higher even than soil type s_1 (Stephenne and Lambin, 2001). (Later we may consider higher yields). The consumable forage of grasses is only 1/3 of the total above ground biomass (FAO, 2001; Stephenne and Lambin, 2001). We assume that yields of grass from land treated with stone bunds will increase at the same rates as the increase in crop yields shown in Table 7.5.

7.7.2 Wood production

Trees are generally more effective than grass in converting deep soil nutrients and water into biomass (Jagger and Pender, 2000). Yield of wood varies considerably due to variations in rainfall and soil type as well as the density and age of trees. The density of trees in the natural woodlands (dominated by acacia) in the Central Highlands is generally very low. Quantitative estimates on tree density and volume of wood in the natural woodlands are almost non-existent. However, one fairly detailed study of acacia woodlands that involved actual cutting and measurement of trees from a stratified sample of the woodlands as well as remotely sensed data has been done for two sub-catchments in the Central and Southern zones (Viti *et al.,* 2001). The study covers about 535 km^2 of which 52.57% was classified as woodlands. The results of this study indicate an average cover of 10% and average age of trees approximately between 6 to 8 years. The estimated average yield of woody biomass is 0.2 m^3/ha/year or, using a conversion factor of 750 kg/m^3, 150 kg/ha/year. About 60 percent of the woodland had a total stock of woody biomass of less than 1500 kg/ha and only less than 5 percent had a stock of more than 4500 kg/ha. The estimated average stock of wood was 1050 kg/ha. Openshaw (1998) presents estimations of woody biomass yields from fully stocked woodlands in Africa for different age groups and varying levels of rainfall. For the average cover and rainfall in the Highlands of Eritrea the yields estimated above are consistent with the results of this study.

The yields from eucalyptus plantations are generally higher than the natural woodlands. Despite the long history of eucalyptus plantations, however, quantitative information on yields from plantations in Eritrea is not available. Estimates in Ethiopia show that the mean annual increments on Eucalyptus plantations vary from 10 m^3/ha/year on poor sites to 57 m^3/ha/year on good soils. Senior students from the Department of Forestry at the University of Asmara were made to estimate the average yield of eucalyptus plantations in two locations in the Central zone. The age of the trees varies from 4 years to 10 years. The average yields in the two locations were 1.10 and 1.90 m^3 per ha/year

(Ermias *et al.,* 2003). These yields are much lower than the estimates of the poor sites in Ethiopia. Since eucalyptus is generally planted on steep slopes for the purpose of soil conservation, we will assume that (the average of) these figures reflect yields on soil type 4. We also assume that the yields on other soil types will vary at the same rate as the yields for crops vary across different soil types.

In addition to wood, grass also grows in natural woodlands and eucalyptus plantations. As the number of trees in natural woodlands is much lower than in plantations, the yield of grass will be higher in the former. Yield of grass from natural woodlands and eucalyptus plantations will be assumed to be 90% and 20% respectively of the yields from grasslands. This is based on the 10% cover in natural woodlands and assuming a 20% cover in plantations.

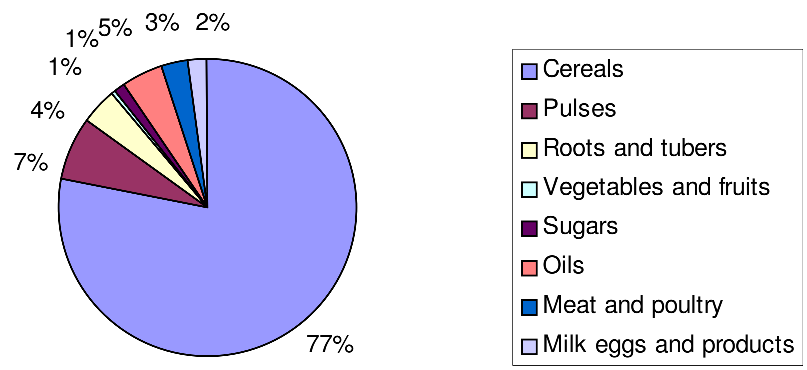
7.8 Food and fuel requirements

7.8.1 Food requirement and consumption patterns

The daily per capita energy requirements vary from one person to the other due to variations in age, sex, body weight and physical activities. Most of the data required to calculate the minimum calorie requirements in Eritrea - such as the age and sex distribution of the population, weight, birth rate, infant mortality rate, patters of physical activities and energy expenditures associated with these activities – are difficult to obtain. Some studies suggest a minimum per capita requirement of 2000 to 2050 calories per day (World Bank, 1996b).

Cereals are the basic staple in all parts of Eritrea. Figure 7.3 shows the consumption patterns in Eritrea. About 78 percent of all energy requirements are covered by cereal consumption, 7% by pulses, 5% by animal products and the remaining 10 percent from oils, sugar, roots and tubers and vegetable and fruits (FAO, 2001). In general, the costs of calories obtained from non-cereal food items are estimated to be about twice the cost of cereal calories (World Bank, 1996b). [Taking average calorie content and average price of the major cereals, the expenditures required to obtain the non cereal calories will be Nakfa 214 per person per year.]

Figure 7.3 Food consumption patterns in Eritrea



Source: FAOSTAT

Other household expenditures include expenditures for basic education, health services and other miscellaneous expenses such as purchases of clothing and soap. The average expenditure on clothing, education, health and other miscellaneous items for poor households in Asmara was estimated to be about Nakfa 100.00 per capita per year in 1996 (World Bank, 1996b). [Taking into account the high rates of inflation since the recent border war, expenditures on the above items will be about 200 per capita per year].

7.8.2 Fuel: level and composition

Traditional fuels (mainly fuel wood, dung and agricultural residues) dominate household energy consumption in Eritrea (see Chapter two). Rural households have even less access to modern fuels and heavily depend on traditional fuels. Table 7.10 below shows the contribution of different types of fuels to the total energy consumption of the rural households in the Central Highlands of Eritrea.

Table 7.10 Per capita energy consumption by fuel type for rural areas of the Central Highlands

	Zoba Debub			Zoba Maekel		
	Qty/person	% Users	MJ of energy/person	Qty/person	% Users	MJ of energy/person
Fuelwood	211.76	95.15	3344.7 (49.5)	134.07	59.41	1322.2 (28.2)
Charcoal	146.01	2.43	102.9 (1.5)	71.28	2.65	54.8 (1.2)
Dung	246.46	67.91	2008.5 (29.7)	299.74	69.4	2496.2 (53.3)
Agr. Resid	139.01	32.09	669.1 (9.9)	106.99	10.88	145.8 (3.1)
Kerosene	15.16	94.22	630.4 (9.3)	19.14	97.94	658.2 (14.1)
Electricity*	18.75	1.00	6.8 (0.1)	1.89	2.0	1.4 (0.03)
LPG	0.00	0.37	0.0 (0.0)	10.69	0.88	4.3 (0.09)
Total			6762.4			4682.7

Source: Based on MOEM (2000).

The average per capita energy use is 4682.7 MJ per year in the Central Zone and 6762.4 MJ per year in the Southern Zone. The composition of fuel also varies between the two regions of Central Highlands. Fuel wood is the dominant type of fuel in Southern zone, where it is used by more than 95 percent of the households and accounts for about 50 percent of energy consumption. Animal dung, on the other hand dominates fuel consumption in the Central zone where it accounts for more than 53 percent of energy consumption. Most households in the Central highlands use kerosene, mainly for lightening purposes. However its contribution to total energy consumption is still very low – about 9 and 12 percent in the Southern and Central zones respectively. The use of electricity and LPG is insignificant accounting for less than 1% of all energy consumption in the rural areas.

The data presented above show that per capita energy consumption increases with the availability of fuel wood and dung. Thus we will use the lower level of energy use (4682.7 MJ per person year) for Embaderho and Zibanuna and the higher level 6762.4 MJ per year) for Maiaha. Moreover, kerosene should cover at least 10% of the required energy, because at least for lighting purpose, it cannot be substituted by the other traditional fuels.

7.9 Some empirical evidences

7.9.1 Fertilizer and crop yield

Yield response to fertilizer application varies from crop to crop. It is reported that in Ethiopia maize has the highest response rate reaching up to 4 fold followed by wheat and barley, which may reach 2-3 fold increases in yields. Taff and pulses were reported to have lower rates with up to 100% and 25-50% respectively (Shank, 1996). The economically optimal rates of application, which depend on fertilizer response of crops as well as the prices of fertilizer and crops, also vary considerably from crop to crop. The following are the optimal economic rate of fertilizer application recommended by the National Fertilizer Input Unit of Ethiopia for maize, taff, sorghum, barley and wheat: 165/80, 130/110, 65/60, 100/100, 120/120 kg of DAP/Urea per ha respectively (Shank, 1996).

There are very few fertilizer trials undertaken in Eritrea. Although fertilizer trials have been underway since 1995 in different parts of the Central Highlands, only two years, 1998 and 1999 had sufficient data that would allow systematic analysis of the effect of the different rates of fertilizer application on crop yields. For other years data were not complete (Barbier, 2001; MOA 2002c). The experiments tested the effects of three levels of Urea (0, 50, 100 kg/ha) and three levels of DAP (0, 50, 100 kg/ha) with a total number of nine treatments. The mean grain yields in quintals/ha from the combined analysis of variance for 1998 and 1999 together and results of a simple economic analysis for each treatment could be found in Barbier (2001). Based on this analysis Barbier (2001) suggested a tentative fertilizer guideline for barley and wheat of 50 kg/ha Urea + 50 kg/ha of DAP to maximize the ratio of returns on cost of production. The suggested economic optimum rates of application, depending on crop and location, are 50 kg/ha DAP + 100 kg/ha Urea, 100 kg/ha DAP + 50 kg/ha Urea, 100 kg/ha DAP + 100 kg/ha. Table 7.11 presents the mean grain yields in various villages of the Central Highlands for three levels of fertilizer application.

Table 7.11 Fertilizer trials for barley and wheat in the highlands of Eritrea 1998 and 1999

Location	Barley (100 kg/ha)			Wheat (100 kg/ha)		
	1	2	3	1	2	3
Teraemni	4.2	11.2	12.3	6.2	10.6	10.8
Adigheda	7.4	11.4	12.3	8.9	13.8	14.7
Dubaruwa	-	-	-	10.4	14.5	15.7
Kisadaro	2.9	11.4	17.0	5.7	13.5	12.5
Shiketi	7.4	14.9	16.4	-	-	-
Serejeka	7.7	15.0	13.3	-	-	-
Tsaedakristian	7.5	13.1	14.4	-	-	-
Himbrti	-	-	-	11.3	17.8	18.0

1 = no fertilizer, 2 = 50 Urea + 50 DAP, 3 = 100 Urea + 50 DAP
Source: Barbier (2001).

The Soil Research Unit of the Ministry of Agriculture has also conducted extensive field level fertilizer trials for three crops (barley, wheat and taff) in various parts of the Central Highlands of Eritrea with the objectives of developing a site-specific and cost-effective fertilizer application rates. The treatments included three levels of Nitrogen (0, 30 and 60 kg/ha) and two levels of phosphorus (0, and 60, 40, 20, or 10 kg/ha) depending on the P level of each site. In total there were six treatments. Apart from some technical assistance by experts, all the trials were undertaken by the farmers under the usual farm management practices.

Both the yields from the control plots and the response to different levels of fertilizer application vary considerably due to variations in soil characteristics, rainfall and crop management. In most cases responses to fertilizer application were high, sometimes exceeding 150 % increase in crop yield. However, as the experiments represent only a single year and due to differences in soil characteristics, rainfall and crop management of the sites, no meaningful conclusions could be drawn.

Similarly, field experiments by the project Sasakawa Global 2000 indicate that the application of 50 kg Urea/ha + 100 kg DAP/ha increased yield of barley between 50 percent and 200 percent in different locations in the CH zone.

Table 7.12 Yield responses by barley to the application of 50 kg Urea and 100 Kg DAP/ha on non-vertisols in Zoba Debub, 1998, Sasakawa Global, 2000.

Sub-Zoba	Yield without fertilizer (100 kg/ha)*	Yield with Fertilizer (100 kg/ha)	
		Mean	Range
Adikeih	6	15	12-20
Senafe	6	18	15-22
Segeneiti	6	17	14-22
Mendefera	6	19	16-22
Areza	6	9	6-14
Dekemhare	6	16	12-20

* Figures are not actual measurements but average yields of the region
Source: Barber (1998)

Despite high variations the limited available evidences show a substantial fertilizer response in the Central Highlands of Eritrea. The fertilizer response of crop yields implied by the yield functions estimated using simulated data (Table 7.5) is in the range of 130 to 250 percent increase. This is considerably higher than the limited evidence from fertilizer trials presented in this section. Thus the crop yields with the use of fertilizer obtained using the TCG were reduced by 40 percent to reflect fertilizer responses under current land management practices.

7.9.2 Estimation of soil loss and run-off

In this section we will combine long-term data from Afdeyu Research Station with a soil erosion simulation model to estimate soil loss and water run-off from the different land categories described in Table 7.1. Soil loss and run-off will be estimated for croplands, grasslands and woodlands. In the following section we will make use of the estimated soil loss and run-off to calculate the impact on crop yield of the construction of stone bunds.

In Section 7.5.1, we have presented a statistically estimated soil loss from croplands using simulated data. However, the simulation model does not provide data for non-croplands. Thus the purpose of this and the next section is: 1) to extrapolate soil loss to other land uses (grasslands and woodlands), 2) compare simulated soil loss with the limited empirical evidence in the Central Highlands, and 3) to estimate impacts of stone bunds on crop yield based on field data which will serve to validate the relationship obtained by statistical analysis of simulated data in 7.4.2.

Soil loss

Accurate measurement and prediction of the rate of soil loss is the first step in estimating the costs of soil erosion and the benefits from undertaking measures to curb erosion. The level of soil erosion in a given area is influenced by a number of factors including rainfall, soil type, topography, and land use and land management. Given the gradual nature of the process, the difficulties in differentiating between the natural and accelerated rate of erosion, and the complexities of temporal and spatial variation, the physical measurement of soil erosion is extremely difficult (Lal, 1990; Eaton, 1996).

Soil erosion is generally more acute in tropical areas where rainfall is more intense and soils are highly erodible due to the relatively shallow depth and low structural stability (Eaton, 1996). However, little reliable evidence exists about the magnitude of the problem. Lutz *et al.* (1994: 274) remarked that aggregate quantitative measures about the extent of land degradation in Latin America "often have weak empirical basis and the studies have generally been scattered and unsystematic". Blaikie (1985) also presented a number of reasons for the absence or unreliability of data on the rate of soil loss in developing countries including lack of trained manpower and sophisticated equipment, which are necessary for a direct measurement of soil loss.

To overcome the difficulties and shortcomings of direct measurements statistical modelling of the process of erosion was developed that can be used to estimate soil loss based on climate, topography, soil properties and land use conditions of an area. The Universal Soil Loss Equation (USLE)[41] has been the most widely used erosion model to predict soil loss (Wischmeier and Smith, 1978) for decades. The parameter values of the factors included in the USLE (R,K,L,S,C, and P) are location specific and need to be calibrated to the specific area to enable reasonable prediction of the rate of soil loss. Hurni (1988) has modified the USLE to fit the Ethiopian conditions (Table 7.13). We will first present the USLE modified for the Ethiopian conditions and use it to extrapolate the soil loss measured in Afdeyu Research Station to lands of different slope classes and land uses.

[41] A Revised Universal Soil Loss Equation (RUSLE) has been developed to improve the USLE and address its criticisms (Renard *et al.,* 1996).

The equation is given as follows:

A = R*K*L*S*C*P
Where:
A = Soil loss (tons/ha/year)
R = Rainfall erosivity
K = Soil erodibility
L = Slope Length
S = Slope gradient
C = Land cover
P = land management

Table 7.13 The Universal Soil Loss Equation adapted for Ethiopia

R: Rainfall Erosivity

Rainfall (mm)	100	200	400	800	1200	1600	2000	2400
Factor R	48	104	217	441	665	890	1115	1340

K: Soil Erodibility

Soil Colour	Black	Brown	Red	Yellow
Factor K	0.15	0.20	0.25	0.30

L: Slope Length

Length (m)	5	10	20	40	80	160	240	320
Factor L	0.5	0.7	1.0	1.4	1.9	2.7	3.2	3.8

S: Slope Gradient

Slope (%)	5	10	15	20	30	40	50	60
Factor S	0.4	1.0	1.6	2.2	3.0	3.8	4.3	4.8

C: Land Cover

Land Cover	Factor C	Land Cover	Factor C
Dense forest	0.001	Dense grass	0.01
Other forest	0.02	Degraded grass	0.05
Badlands hard	0.05	Fallow Hard	0.05
Badlands soft	0.04	Fallow Ploughed	0.60
Sorghum, Maize	0.10	Ethiopian Taff	0.25
Cereals	0.18	Continuous fallow	1.00
Pulses	0.15		

P: Management

Land Management	Factor P	Land Management	Factor P
Ploughing up and down	1.00	Ploughing on contour	0.90
Strip Cropping	0.80	Intercropping	0.80
Applying Mulch	0.60	Dense Intercropping	0.70
Stone Cover (80%)	0.50	Stone Cover(40%)	0.80

Source: Hurni (1988).

Estimations of the rate of soil loss in the Highlands of Eritrea vary considerably (see Section 2.4). Apart from the fact that these figures were based on debatable assumptions, such an average estimate for the whole of highlands is far from sufficient for meaningful economic analysis. Soil loss data for various categories of soil, topography and land use and land management is important because the rate of soil loss varies considerably due to variations in the above factors.

Annual soil losses and run-off from experimental plots in Afdeyu Research Station are the only empirical data we have for the Highlands of Eritrea. Four experimental plots were established to study the effect of different soil conservation structures on soil loss and run-off. The experiments in this research station were done only on croplands with a slope of 31 percent. These empirical results, however, provide a basis to test the accuracy of the prediction of soil loss estimates using the USLE modified for the highlands of Ethiopia by Hurni (1988) and serve as a starting point to extrapolate soil loss to lands of different slope categories, different land use and land management practices.

Table 7.14 shows that the annual rate of soil loss from the experimental plots for the period 1988 to 1998 varies considerably probably due to differences in magnitude, distribution and intensity of rainfall across the years. The average annual soil loss from the control plot is 45.1 tons/ha. The establishment of stone bunds has reduced soil loss by about 80 percent. The application of level-double ditch and Fanya-juu conservation structures has reduced soil loss by more than 90 percent.

Table 7.14 Annual soil loss (t/ha) in Afdeyu catchments 1988-1998

Year	Control plot	Stone bund	Level double ditch	Level Fanya-juu
1988	108.1	37.6	23.6	20.1
1989	2.7	0.5	0	0.2
1990	8.6	1.5	0.2	0.3
1991	20.3	8.4	1.5	4.6
1992	34.2	5.7	0.7	0.9
1993	10.7	0.7	0.0	0.3
1994	6.9	0.0	0.0	0.0
1995	84.0	19.7	5.7	4.7
1996	62.6	21.9	3.3	1.9
1997	54.1	3.1	0.0	0.0
1998	62.5	2.7	1.2	1.7
Mean*	45.1	9.3 (79.4%)	3.3 (92.7%)	3.2 (93%)

* Figures in bracket are percentage reduction in soil loss.

Source: Stillhardt *et al.* (2002), ARS (unpublished reports)

We now estimate the rate of soil loss using the USLE modified for Ethiopian conditions and compare it to the actual (measured) soil loss from the experimental plots. The parameters needed for the estimation are determined based on Table 7.13 as well as climate, soil, landscape, land use and land management information of the research plots presented below (Stillhardt *et al.,* 2002).

	Parameter-values
Slope = 31%	S = 3.08
Soil type: Cambisols (red brownish colour)	K = 0.28
Slope length: 30 meters	L = 1.2
Average rainfall (11 years included in table 7.16): 473mm	R = 258
Types of crops: often cereals	C = 0.18
Management Factor: Ploughing on contour	P = 0.9

Calculated soil loss = 43.25
We can see that the actual average soil loss (45.1 tons/ha/year, see Table 7.14) is similar to the soil loss predicted by the USLE, which is 43.25. Thus it may be justified to use the USLE to estimate the rate of soil loss from different slope categories and different land uses.

Table 7.15 shows the estimated rate of soil loss from different soil types and land uses based on the parameters in the USLE in Table 7.13. We first adjust the estimated soil loss (43.3 t/ha/year) for soil types s_1, s_2 s_3 and s_4, which have an average slope of 4%, 12%, 22%, and 40%. According to the USLE (A = R*K*S*L*C*P) the estimated soil loss is (258*3.08*0.28*1.2*0.18*0.9 = 43.3). This refers to a slope of 31%. To estimate soil loss from other slope categories we replace the S factor with the appropriate parameter from Table 7.13. For example, to calculate soil loss from s_1 (which has an average slope of 4%) we replace the parameter of factor S, which was 3.08 by 0.32[42]. This gives us 4.49 t/ha/year.

Similarly we can change the land cover factor C to estimate soil loss from grasslands and woodlands. Since cereals are the major crops in the research area, the C factor used was 0.18. This is replaced by 0.05 for grassland and 0.02 for woodlands. For example, to calculate soil loss from grasslands of soil type s_4, we divide the soil loss from croplands of soil type s_4 (53.35) by 0.18 and multiply it by 0.05.

Table 7.15 Soil loss from different land categories and land use (tons/ha)

Land type (slope)	Cropland	Grassland	Woodlands
s_1 (0% - 8%)	4.49	1.24	0.50
s_2 (8% - 16%)	17.41	4.80	1.60
s_3 (16% - 30%)	34.25	9.51	3.8
s_4 (>30%)	53.35	14.81	5.92

Source: Calculated based on Table 7.13 and Table 7.14.

42 As the parameter values for the factors are not continuous we assume a linear relationship with in each range.

Run-off

Another important benefit from the construction of stone bunds is moisture conservation. The total amount of run-off from the experimental plots in ARS is presented in Table 7.16.

Table 7.16 Rainfall and annual run-off (mm) on experimental plots (1988-1998, Afdeyu)

Year	Rainfall	Control plot	Stone bund	Level double ditch	Level Fanya-juu
1988	582.9	326.7	224.4	244.4	172.5
1989	258.8	31.9	9.5	5.0	6.6
1990	244.1	90.8	15.7	7.7	8.1
1991	320.9	150.8	78.0	23.7	63.5
1992	466.5	254.0	107.4	29.1	34.4
1993	443.9	137.8	17.6	12.2	14.3
1994	533.9	254.5	40.7	30.8	23.2
1995	658.0	248.4	148.4	108.7	106.4
1996	552.0	294.7	189.0	92.6	70.2
1997	575.0	257.3	84.6	22.0	24.7
1998	558.1	251.3	90.5	58.0	64.1
Mean (% of rainfall	472.9	208.9(44%)	91.4(19%)	57.7(12%)	53.5(11%)

Source: Stillhardt *et al.* (2002), ARS Reports.

When no soil conservation measures are undertaken, on average about 44 percent of the rainfall is lost as a surface run-off. This is reduced to 19 percent when stone bunds are applied. The amount of run-off from lands of different slope categories and land uses can be extrapolated in the same way soil losses were estimated in the previous section. This is based on the assumption that soil loss and run-off will vary in the same proportion across the various soil types and land use activities. For example, to arrive at run-off from croplands for soil type s_1, we divide the average run-off from the control plot by 3.08 (the slope factor associated with the slope of the experimental plots) and multiply it by 0.32, the slope factor associated with soil type s_1.

Table 7.17 Annual run-off from different land categories and land use (mm)

Land Type	Cropland	Grassland	Woodlands
S1	21.70	7.73	3.00
S2	83.74	23.17	9.32
S3	165.50	46.00	18.36
S4	257.70	58.00	23.20

Source: computed based on Table 7.13 and Table 7.16

Table 7.17 shows the predicted surface run-off from land of different slopes and land use when no soil conservation measures are applied. The application of soil conservation measures makes more water available for use by crops. The average run-off from the plot where stone bunds were applied has declined by

56 percent. Assuming that the run-off from all slope categories will decline at this rate with the application of stone bunds, the additional water that will be available annually for use by crops in soil types s_1, s_2, s_3, s_4 will be 12.2, 46.9, 92.7, and 144.2 mm respectively.

7.9.3 Soil conservation and crop yield

The relationship between erosion and crop yield is a very complex one. Various studies on erosion –yield relationships in the Ethiopian highlands show considerable variations. They range from a decline of 3% per annum to 0.12 % per annum (1984; Hurni, 1985; Sutcliffe, 1993; Bojo and Cassels, 1995). Most of the variation was due to the different rates of erosion used by the authors. Those studies that resulted in a lower yield decline applied a soil life cycle model developed by Stocking and Pain (1983) as the analytical framework to establish the minimum depth required for cultivation of different crops as well as the maximum depth beyond which erosion does not immediately affect soil crop cultivation. Thus, in addition to using lower rates of soil loss, soils lost from deep soils (greater than 100 cm) were considered to have no effect.

There are no studies that relate crop yield to soil erosion in Eritrea. Long-term monitoring of annual crop yield and biomass production in the Afdeyu catchments, however, provides important data which could be analysed statistically to relate soil depth to crop yield (Araya, 1999). These types of analyses were also done in Ethiopia (Hurni, 1985; Shiferaw and Holden, 1999). The variables, which affect crop yield, include soil depth, rainfall, soil type, and the crop management system practised (e.g. number of weeding, number of ploughing, crop rotation system and the use of fertilizers).

Soil erosion also affects crop yield due to its effect on the moisture available to crops. The effect of moisture conservation due to the construction of soil conservation measures on crop yield depends on climatic conditions. Thomas and Ademseged (1984:3) noted that while the moisture conservation effect of soil conservation measures may not lead to any yield difference in wet years, in dry years it could be a “difference between a crop and no crop”. Others have found a negative relationship between rainfall and crop yield in the Highlands of Ethiopia, where rainfall is high (Demeke, 1998; Shiferaw and Holden, 1999). Thomas and Ademseged (1984) suggest that 25 percent yield increase due to moisture conservation from the construction of stone bunds in dry areas should be reasonable estimates.

Harvest samples have been collected for more than one decade in the Afdeyu Research Station. Variables which affect crop yield such as rainfall, soil depth, slope, and crop management system practised (e.g. number of weeding, number of ploughing and type of fertilizer applied) were available for the years 1987 to

1998[43]. This provides data on many of the relevant variables. However, with respect to fertilizer only the type of fertilizer and not the quantity applied is presented. Table 6 provides a summary of the relevant variables obtained from the harvest samples collected between 1987 and 1998. Only barley and wheat, which are the major crops in Afdeyu, had sufficient observation for statistical analysis.

A population model for the yield function may be proposed as follows:

$$Ln(Y_i) = \beta_0 + \beta_1 ln(R) + \beta_2 ln(D) + \beta_3 ln(S) + \beta_4 P + \beta_5 F + \beta_6 W + \varepsilon_I \qquad (2)$$

Where Y_i is yield of the i^{th} crop (kg/ha); R is rainfall (mm); W, P and F are dummy variables referring to crop management practices (F = 1 if fertilizer is applied, P = 1 if number of ploughing > 2, and F = 1 if fertilizer is applied); β_i are the respective partial regression coefficients; and ε_i is the population error term. It is assumed that the error term is normally distributed with a mean of zero and has a constant variance. All rainfall, soil depth, and the dummy variables included are expected to be positively related to yield.

Table 7.18 Descriptive statistics of variables from harvest sample (Barley 1987-1998)

	Rainfall (mm)	Slope (%)		Soil depth (cm)		Weeding (no)		Ploughing (no)		Yield (kg/ha)	
		Barely	Wheat	Barely	Wheat	Barely	Wheat	Barely	Wheat	Barely	Wheat
Mean	472.9	9	9	23.40	21	0.97	0.97	2.25	2.25	1958	1240
Max	582.9	45	38	42.00	41	3.00	3.00	5.00	5.00	8700	3500
Min	244.1	0	0	23.38	20	0.00	0.00	1.00	1.00	100	150

Sample size: Barley = 144 Wheat = 110
Source: Harvest sample reports of ARS.

A Cobb-Douglas yield function is estimated relating crop yield of barley to rainfall, soil depth, slope, number of weeding, number of ploughing, and application of fertilizer. All signs of the variables except slope were positive and significant. The adjusted R^2 was 0.47 showing that the variables included in the yield function explained 47 percent of the variations in yield. The coefficients of rainfall and soil depth show that, other things being equal, the yield of barley declines by 1.18 percent per one percent decline in rainfall and by 0.38 percent per one percent decline in soil depth.

The Cobb-Douglas functional form did not provide a good fit to the wheat yield function. Thus simple linear functional form is estimated. Although most variables did not have positive signs and/or were not significant, rainfall and soil depth were positive and significant. The adjusted R^2 was 0.18 showing that rainfall and soil depth together explain 18 percent of the variations in yield. The

[43] Yield data for 1992 and 1993 were missing and are therefore not included in the analysis.

overall F-test is highly significant for both barley and wheat. The results show that yield of wheat declines by 170 kg/ha per 100 mm decline in rainfall and by 29.4 kg/ha per one cm decline in soil depth. Table 7.19 shows the results of the production functions for barley and wheat.

Table 7.19 Wheat and barley production functions

Variables	Barley		Wheat	
	Coefficient	t-statistics	Coefficient	t-statistics
Constant	-1.94	-1.84*	-216.74	-0.94
Rainfall	1.18	7.13***	1.70	3.27***
Soil Depth	0.38	2.38**	29.4	2.25**
Manure	0.29	2.43**		
First weeding	0.26	1.96*		
Second weeding	0.34	1.86*		
Ploughing	0.13	2.52**		
Number of observations	144		110	
Adj- R^2	0.47		0.18	
Durban-Watson test	1.90		1.25	

* $p < 0.1$
* $p < 0.05$
* $p < 0.01$

Table 7.18 indicates that soils are very shallow in the Afdeyu Catchments. Considering an average soil depth of 40, 30, 20 and 10 cm for soil types s_1, s_2, s_3 and s_4 respectively, and the yield functions for barley and wheat, we estimate crop yield with and without the application of stone bunds for an average annual rainfall of 472.9 mm. As most fields in the Afdeyu Catchments are treated with stone bunds, the estimated yields better reflect yields when stone bunds are applied. Based on the soil loss and run-off for the different soil types presented in Table 7.15 and Table 7.17, and the effect of stone bunds in reducing soil loss and run-off, soil depth and amount of rain available for plants were adjusted to estimate crop yields when stone bunds are not applied. Table 7.20 shows estimated crop yields of barley and wheat when stone bunds are applied and not applied.

Table 7.20 Barley and wheat yields (kg) with and without the application of stone bunds

	Barley			Wheat		
	No Bund	Bund	% Change	No Bund	Bund	% Change
S1	1552	1602	3.22	1741	1763	1.26
S2	1264	1436	13.61	1383	1469	6.22
S3	942	1231	30.68	1005	1175	16.92
S4	598	946	58.19	617	881	42.79

Most of the variations between yields with and without the application of stone bunds are due to the effect of bunds on moisture conservation rather than the effects on soil depth. As the water conserved and made available to crops by the application of stone bunds are higher for the steeper slope land types (because initial run-off is higher), yield increases are higher for these land types.

However, these yields need to be adjusted for the area occupied by the conservation structures, which of course, are higher for the steeper slopes.

The area of land occupied by stone bunds depends on the length of bunds in each soil type and the area occupied by each bund, which is about 0.8 meters for stone bunds (John 1988). The length of bund required in each soil type has been discussed earlier (see Table 7.3). Table 7.21 shows the percentage of area occupied by stone bunds for different land types.

Table 7.21 Area occupied by stone bunds

Soil type	Distance between bunds (m)	Length of bund (km/ha)	Area occupied by bunds (%)
s_1	25.0	0.4	3.6
s_2	8.3	1.2	9.6
s_3	4.3	2.3	18.4
s_4*	4.0	2.5	20.8

* A horizontal spacing of 4 meters has been suggested as the minimum distance between bunds

7.10 Prices

As stated earlier, rural households in the Central Highlands engage in the buying and selling of crops, livestock, agricultural inputs, and other consumer goods and services. The prices of crops and livestock vary considerably from one region to the other and during different seasons in a given year. In an average year, households in the Central Highlands of Eritrea harvest their crops in October/November and consume their production with in four to six months. To cover their food needs for the rest of the year, households rely heavily on the market. The prices households receive for their products (producer prices) and the prices they pay (consumer prices) also differ due to variations in supply and demand in the different seasons of the year as well as due to the marketing costs involved. Since domestic production in an average-rainfall-year covers less than half of national demand, crop prices are highly influenced by the amount of commercial food imports and food aid.

Crop and livestock prices have increased considerably since 1998. Rising prices reflect reduced cereal supplies due to poor domestic production, border closures with Ethiopia and Sudan which have significantly reduced informal cross-border flows, and constrained capacity to import due to foreign exchange constraints. Other prices such as the price of wood, kerosene, vegetables and wages have also increased considerably since 1998. The evolution of crop and livestock prices during the last 10 years is presented in the Appendix 3 (Figure A1 and Figure A2).

The prices used in this study are average prices of the year 2002, the year we carried out our field work. The selling and buying prices for crops, livestock and fuel wood for the study villages are estimated based on the 2002 prices in the nearest town and marketing costs (which include transportation and storage costs and other costs)[44]. Since it is difficult to anticipate how the relative prices of the various prices included in the model would change under normal conditions, we use constant prices through out the planning period. The prices used in this study are presented in Table A7.

Reliable estimate of the discount rate is very difficult to obtain. We assume that the discount rate is equal to $1/(1+r)^t$, with r the interest rate and t is time. The official banks' interest rate for lending money is 12 percent and the interest rates of the two microfinance institutions[45] in the country are 14 and 16 percent. The official rate is used in this study but sensitivity test are conducted for higher rates of discount (see Section 8.6 and Figures A4 and A6 in Appendix 4).

7.11 Conclusions

In this chapter we have estimated the main parameters of the model presented in Chapter six. Particular emphasis was given to the estimation of availability of labour and labour requirement for various activities in different periods of the year; as well to the estimation of crop yield soil and loss from different land categories as a function of different types of fertilizers and soil conservation.

The USLE adapted for Ethipian conditions was used to extrapolate the limited data obtained from Afdeyu Research station to different land uses and to lands with different slopes. The estimated rates of soil loss obtained using the USLE for the similar conditions of the plots in the Afdeyu Research station were very similar to the actual rates of soil losst from the experimental plots.

The TCG developed for the highlands of Ethiopia, which are similar to the Highlands of Eritrea, was the major source of data for the yield and soil loss data. The data obtained using the TCG were compared to the limited empirical data from the country. The yields estimated using the TCG were generally higher than the yields observed in the study areas mainly due to the choice of optimal sowing date, average rainfall etc. Although we have reduced the yields to reflect the present situation, the TCG was nevertheless an invaluable source of data to obtain crop yields when different types of fertilizers and different

[44] The estimated marketing costs, defined as the difference between the farmgate price and market prices, for the three study villages are presented in Table 8.1.
[45] The two microfinance programs in Eriterea are the Southern Zone Saving and Credit Scheme and the Saving and Micro Credit Program (see Mehrteab 2005).

types of soil conservation techniques are used. As the production of empirical data for various regions and various land categories in the country is unlikely in the foreseeable future, calibrating these models by agricultural scientists for the Eritrean situation can provide a valuable source of information.