TECHNOLOGY AND POLICY IMPACTS ON ECONOMIC PERFORMANCE, NUTRIENT FLOWS AND SOIL EROSION AT WATERSHED LEVEL: THE CASE OF GINCHI IN ETHIOPIA*

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Abstract

A dynamic bio-economic model is used to examine natural resource use, the resulting nutrient balances and economic outcomes in a poor country under a range of technological and policy intervention scenarios. With limited technological intervention over a twelve year planning period, incomes rise by 50% from a very low base and average per ha nutrient balances stand at –58kgs for nitrogen, -32kgs for phosphorous and –114kgs for potassium. Associated soil losses are 31 tons per ha. With a set of new technologies involving use of new high yielding crop varieties, agro-forestry, animal manure and inorganic fertilizers, construction of a communal drain to reduce water logging and some limited land user rights, results show a tenfold increase in incomes, 20% decline in aggregate erosion levels and an increase in the dependence on livestock for dung manure, oxen draft, milk and ready cash over time. Moreover, a minimum daily calorie intake of 2000 per adult equivalent is met from on-farm outputs and per ha nutrient balances after intervention are as low as –25kgsN, -14kgsP and –68kgsK on the average. There is hence an obvious reduction in nutrient losses despite the higher reliance on the watershed for subsistence food requirements. The bias towards replenishment of nitrogen and phosphorous nutrients at the expense of potassium may, however, not be resolved. Emissions (leaching, gaseous losses, and erosion) could be higher than immissions (atmospheric deposition, nitrogen fixation) in both situations. From a policy perspective, these results imply an increasing need for a more secure land tenure policy than currently prevailing and provision of credit to ensure uptake of the above land management technology packages. They also imply a shift from a general approach to land management to a relatively more site specific approach that emphasizes spatial and inter-temporal variability in input use based on land quality. Such variable rate technology may be an efficient nutrient management strategy as it enables farmers to apply optimal rates of fertilizer for each field and in each period. Moreover, residual nutrient loading is simultaneously reduced. Implementation of such a strategy may be difficult in a developing country situation but an attempt to do so may yield results that are significantly better than at present.

(Key words: Bio-economic model, watershed, resource degradation, nutrient mining, nutrient balances, erosion, dynamic programming, Ethiopia).

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1. INTRODUCTION

Land degradation, low productivity, poverty and declining human welfare are the dominant problems of the crop livestock production systems prevalent in most parts of the tropical highlands. This study examines economic outcome and nutrient balances arising from the driving forces behind these problems using a watershed framework of analysis as opposed to a farm household approach and applying a bio-economic model as opposed to a purely economic or biophysical model. The model is validated in the Ginchi watershed in the central highlands of Ethiopia. The current situation of limited technological and policy intervention in the watershed is compared with the situation involving single and multiple interventions. Technology strategists are arguing for a shift in focus from increasing agricultural production per se through overcoming soil constraints to fit plant nutrient uptake by use of purchased inputs, to a minimization of external inputs use and maximization of their efficiency (e.g., Sanchez, 1994). Following such an approach this study utilizes a nutrient balance monitoring technique (van den Bosch et al., 1998) to gain insight on the effects of proposed technology and policy interventions on the gains and losses of major nutrients in the watershed and accompanying economic performance. Hence judicious measures that manipulate nutrient flows to result in reduction in nutrient losses or increase in nutrient gains are explored.

Two versions of the bio-economic model are generated: a) a static goal programming version b) a dynamic non-linear mathematical programming version. The static goal programming approach simultaneously optimizes both environmental and economic goals of the watershed and its results are used to validate the dynamic model. The dynamic model optimizes an aggregate watershed utility function that is indirectly linked to the biophysical aspects of the watershed through an exponential soil loss-yield decline model with single year time lags. Soil losses in one year determine yields of various crops in the following year given the ameliorative effects of chemical and dung fertilizer. Both versions of the model take into account seasonality in input and output supplies, labour substitutability, the various roles of gender, crop and livestock constraints, minimum household food requirements, forestry activities as well as the biophysical aspects of soil erosion and nutrient balances arising from these activities.

Cross-sectional socio-economic and biophysical data from four land categories found in the watershed for the years 1995, 1996 and 1997 are used to test the model and are supplemented with on-station experimental data. Output from the validated dynamic model is then used to generate nutrient balances arising from the interactions and interrelationships between technological and policy interventions on one hand and biophysical and human factors on the other.

Part two of the paper gives a background of the degradation problem in the Ethiopian highlands and the specifics of Ginchi watershed, part three outlines the analytical model while parts four and five present the results and policy implications, respectively.

2. BACKGROUND

The Ethiopian highlands, lying at about 1500m above sea level, are some of the most severely denuded landscapes in the world. They comprise 46% of the country's landmass and are home to 88% of the 60 million total population (Shiferaw and Holden, 1998). Agricultural productivity is low. Hence 80% of the population employed in this sector generates less than 50% of the GDP. These low productivity levels continue to decline due to land degradation. Current estimates of soil loss from cropped areas stand at 42 tones per ha per annum (Hurni, 1987), while total soil loss from the highlands are estimated at 1900 million tons per annum (FAO, 1986). Ginchi watershed typifies the degradation problem in the Ethiopian highlands and similar highlands elsewhere . Located in the central highland massif, this watershed has experienced sizeable degradation over time. Evidence shows that in 1950, only 34% of the watershed were under crops while 60% was under pasture and woodland. The remaining 6% were under communal casual road and paths. In 1990, the situation had totally reversed. Crops are now produced on over 61% of the land area, while pasture and woodland have declined to below half their previous sizes. The result has been severe erosion and drastic declines in crop yields and animal productivity. The bottomlands of the watershed also suffer from intense waterlogging at the beginning of the rainy season due to the predominantly clayey vertic soils.

To arrest land degradation (nutrient mining and soil erosion) and revitalize the mixed crop-livestock production system in the highlands, a consortium of research and development institutions under the Joint Vertisols Project (JVP) developed a package of production and conservation technologies. The package includes an improved animal drawn equipment (the Broad Bed and Furrow Maker or the BBM) for drainage, new crop varieties and related agronomic practices, forage and agro-forestry. Adoption of new high yielding crop varieties would require higher amounts of chemical and organic fertilizers, hence more cash and/or access to credit. Also improved drainage of the lowland Vertisols through adoption of the BBM plough requires more animal draught power, and its success would depend on construction of drainage channels to drain off excess water from the individual farm plots to the river channel or to a communal drain. Construction of both the feeder and communal drains as well as their maintenance would require collaborative action at the community level. This would put pressure on the available amount of human resources, especially labour and cash endowment. Similarly, introduction of new breeds of livestock such as crossbred cows would call for higher amounts of animal feeds with higher nutritive value than is locally available. Given the already scarce natural sources of animal fodder in the area, higher pressure on the existing scarce pasture would be experienced. Farmers must therefore adopt a pasture management strategy that improves pasture productivity.

This study aims at determining the most cost effective strategy of raising the watershed’s income and nutrient gains and/or reducing their losses so as to enhance productivity of the crop-livestock system over time in a typical highland watershed in the Ginchi area.

3. ANALYTICAL MODEL

To date, most studies seeking to analyze the impact of technology on the human needs and environmental concerns utilize farm household models (Nakajima, 1986; Shiferaw and Holden, 1998). Assessment of production and conservation technologies at a household level is, however, too restrictive as it ignores the natural delineation of the landscape, and hence the biophysical scale of the problem, resource multi-functionality, multi-dimensional trade-offs and importance of community participation in solving general externalities arising from household agricultural production (Rhoades, 1998). Household decisions include communal considerations at a landscape level, especially where a community participatory management approach is in place. Aggregation of household decision making at a watershed (landscape) level and use of a holistic approach to model natural resources in a manner that surpasses the capacity of a household level model are viewed as better alternatives. Dynamic bio-economic models are considered as one such approach (Hazell, 1998). They may, however, suffer from aggregation problems associated with averaging resource availabilities including other structural parameters. The assumption of a perfect match between the physically delineated land unit (watershed) and the community utilizing it is also not likely to hold everywhere. Thus the community living in the watershed may own land of different quantity and quality outside the watershed boundary and vice versa. On the average, however, the amount and quality of land owned outside the watershed by the watershed residents and the amount owned inside the watershed by non residents may cancel out. In Ginchi watershed, these limitations are minimized by the high homogeneity of the community (in terms of quantity and quality of resource endowment especially land) as Gryseels et al. (1983) noted : " Membership in the PA[1] implies access to land for communal and individual cultivation, with the size of the individual holding determined mainly by the size of small holder family and the total land area and mix of land qualities available to the PA.". High inter-household interactions in terms of communal labour and animal draft sharing is also observed, increasing further this homogeneity and hence justifying the assumption of a single decision maker at the watershed level resulting from the aggregation of individual household level decisions.

3.1 Ginchi watershed empirical bio-economic model

For the sake of brevity, only the dynamic mathematical programming version of the bio-economic model is presented here. The dynamic model considers a watershed aggregate utility maximization objective consisting of three basic components: cash income, leisure and basic food requirements. For simplicity, food requirements are assumed to be pre-determined by size and composition of population, and hence are treated as scalars in the situation with limited intervention. In the multiple intervention scenario food requirements constraints are raised to levels that ensure a minimum daily calorie intake of about 2000 per adult equivalent. Teff grain minimum consumption requirement is set to progressively increase to cater for any in-migration into the watershed and expected increases in consumption of staples associated with rising incomes of a poor community. The full effects of population growth and possible structural change in employment patter over long term are not analyzed in this paper.

Ordinarily, leisure and income decisions are non-separable. In Ginchi watershed, where 90% of the community belong to the Orthodox Church, religious holidays account for almost half the normal working days in a year. These holidays are strictly adhered to and hence must be subtracted to get actual number of available working days. Any day that is not a church holiday is efficiently used for farm work. Leisure is thus a component of the church holidays and assuming strong separability of the utility function, it is conveniently assumed to be a static sum entrenched in the church holidays. Holding church holidays constant leaves profit or net cash income as the only argument of the utility function. This is a constrained utility function as leisure is constrained to be greater than would be preferred in the absence of so many holidays. Risk[2] is not incorporated due to limited time series data and the large size of the holistic model. The model is specified as follows:

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[1] PA refers to Peasant Association. These are government administrative units at village level headed mainly by a council of village elders and comprising mainly of farmers living in the area

[2] One caveat of this formulation is its assumption of perfect knowledge of market prices and yields (i.e. certainty), with limited explanation of how income from each activity varies across time or how the individual activities interact to produce variable aggregate incomes. Use of cross sectional data to calculate risk is possible but it ignores inter annual price variation (Ciriacy-Wantrup, 1968). The formulation also assumes that farmers in the watershed explicitly portray

Let aggregate watershed utility at time t be:

$$U_t = \sum_{i=1}^{P}(g_{it}.\ \lambda_i Y_{it}) \quad + \quad \sum_{i=p+1}^{S} P_i.(L_{it}-X_{it}) \qquad t = 1,\ldots,T \tag{1}$$

$$g_{it} = (P_{it}.Q_{it}) - (P_{ct}.\ X_{cit}) \tag{2}$$

$$0 \le \lambda_i \le 1 \text{ and } \sum \lambda_i = 1 \tag{3}$$

$$\text{Maximize } \sum_{t=1}^{T}(1/(1+\tau))^t U_t \tag{4}$$

Subject to:

$$\sum_{i=1}^{P} a_{cit}.Y_{it} \le X_{ct} \qquad c = 1,\ldots r; \tag{5}$$

$$Y_{it} \ge 0, \qquad i = 1,\ldots s; \tag{6}$$

$$Q_{it} = \sum q_{ibt}.h_{ibt} \text{ for activities 1 to m and for all land types i.e. b} \tag{7}$$

$$q_{ibt} = \phi(X_{1it},\ldots,X_{cit}).e^{-\alpha ib\beta bt-1} \tag{8}$$

$$\beta_{bt-1} = \sum_{t=1}^{t-1}(E_{bt}/\ W_b) \tag{9}$$

$$E_{bt} = \sum_{i=1}^{I} K_{ibt}.N_{ibt}.R_t.D_t.Z_t.S_t \tag{10}$$

where: b refers to land type or category, activities i =1 to j are crop and pasture; activities i =j+1 to m are planted trees; activities i =m+1 to p are livestock and livestock products; and activities i =p+1 to s are leisure activities. At any time t, Y_{it} is the level of activity i; g_{it} are the per unit net returns from activity i ; Q_{it} is output from activity i from all the land types; λ_i is the weight given to activity i based on its preference by the farmer[3]; τ is the discount rate; a_{cit} are the technical coefficients of production ; X_{cit} is the total quantity of input c (dung manure, chemical fertilizer, labour etc.) per unit of activity i; q_{ibt} are yield per hectare of crop, hay, trees and pasture activities on land type b in year t; h_{ibt} are hectares under activity i in land type b in time t; e is the natural log; $\alpha_{\square b}$ are crop specific coefficients varying with land use activity i and land type b (i.e. slope, soil type and depth); and β_{bt-1} is the cumulative soil loss in tons per ha for the preceding t-1 years on land type b. Cumulative soil loss is arrived at by summing over the past years, E_{bt} values. These are essentially annual soil loss values estimated by the USLE Model. E_{bt} is thus the level of net erosion after considering soil deposition on land class b while W_b is the watershed area of type b soils in hectares; K_{ibt} is the land cover by activity i on land class b; N_{ibt} is the management of activity i on land class

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an optimization behavior. This may not be the case in all instances and hence some of the model results may require external intervention to be realized.

[3] Farmers prefer activities that are not only less risky but are also culturally acceptable based on their traditions.

b; R_t is the rainfall ; while D_t , Z_t and S_t are the soil erodibility, the slope (gradient) factor and the slope length respectively.

The watershed was delineated into four land categories, A, B, C, and D, based on slope and soil type (i.e. b= A, B, C and D) . Land type A are Vertisols of 0-4% slope, Land type B are Vertisols of 5-9% slope, Land type C are alfisols of 10-15% while land type D are acrisols of over 20% slope. USLE's inherent weakness is that being designed for estimation of soil loss on fairly homogeneous plots, it fails to measure soil deposition occurring in a watershed with different land forms and slope. Division of land into land classes was aimed at reducing considerably this weakness of the USLE. Each land type was observed to generally slope towards a riverine. Hence most of the eroded soil was deposited in the water channels and carried away by the river. Gross soil loss on each land type was thus equal to net soil loss on these land types given the negligible possibility of soil deposition.

The model utilizes a dynamic mathematical programming optimization procedure to adjust yields every year as a function of cumulative soil loss in the past years as reflected in equation (8). Crop yields over the 12 year planning horizon are determined based on projected cumulative soil erosion as indicated above. The appropriate function relating crop yield to cumulative soil loss for soils in the watershed is the modified version of the model developed by Lal (1981) and used by Ehui et al., (1990) and Bishop (1995). In this study, yields are expressed as:

$$q_{ibt} = \phi(.)\ e^{-\alpha ib\beta bt-1}$$

The function $\phi(.)$ refers to yields without soil erosion risk (effects) taking into account crop management practices, application of dung and artificial fertilizer use. $e^{-\alpha ib\beta bt-1}$ expresses the decline in yields due to cumulative soil loss effects. With observed data on yields (both with and without soil loss) and cumulative soil loss, α_{ib} may be determined for each crop activity i and for each land category and slope. This is achieved by rearranging the expression and solving for α_{Ib} assuming that q_{itt},, $\phi(.)$ and β_{bt-1} are known from observed data. The mean value of α_{ib} values obtained for each set of the three variables above may then be plugged back in the model for projection purposes. However, since it is rare that q_{it},, $\phi(.)$ and β_{bt-1} are known before hand for any site and at any time, an econometric approach is used to regress data on yields of crop i against varying levels of natural soil erosion. This involves generating the relevant data by setting up agronomic experiments in which all the crops under investigation are planted on side by side plots of the same slope and treated with the same varying levels of per annum soil erosion under the same management conditions (i.e. same rates of dung manure and chemical fertilizer application as well as other crop husbandry practices).

Lal (1981), used this approach to estimate eight equations for eight crops and for four slopes (1, 5, 10, 15%) of alfisol soils in Nigeria. The estimated coefficient for (α) ranged between 0.002 and 0.036 for peas (legumes) and 0.003 and 0.017 for maize (cereals). All except one of the alpha coefficients were significant at 5% level. For the Ethiopian conditions, particularly the study are, no experimental studies had been carried out to capture this relationship, i.e. soil loss-yield decline on the various slopes of the watershed. However, conditions in the two sites (IITA, Ibadan and Ginchi) have some resemblance in the sense that they both have soils of low erodibility and experience highly erosive climatic regimes with intense amounts of variable rainfall. It is hence assumed that crop yields in Ginchi are no less sensitive to soil loss than they are in Nigeria, although actual soil loss rates may vary.

Secondly, the functional form of the model gives more weight to loss of the first top layers of the soil that are universally known to be more fertile than subsequent layers. Hence incremental yield losses gradually decline with cumulative erosion (Bishop, 1995). These two factors justify the use of this model to estimate yield declines due to cumulative soil loss in Ginchi and other sites too. This model, (often referred to as the Lal (or IITA model)) is nevertheless modified to take into account the fact that crop yields are not equally sensitive to soil loss across all the land types in an area such as Ginchi watershed but rather, may vary across soil types and slope among other factors. Based on expert judgement and intuition, the exponential coefficient α_{ibi} is varied by crop type and soil class and depth to attain a range of penalties on yields that are assumed to encompass the true impact of soil loss (Bishop, 1995). Thus for each crop type planted on different slopes or land class, α_{ibi} is varied to capture the yield decline differential due to slope and soil depth differences. The range of coefficients used in the Ginchi bio-economic model lie within the range of those derived by Lal (1981) for the broad categories of crops i.e. legumes and cereals.

One advantage of this model's functional form is that it may assume different elasticity relationships between cumulative soil loss and yields. In the Ginchi model, it is specified as a constant elasticity. Hence a unit of soil loss in the first and the tenth year would result in the same percentage decline in yields respectively. If for some reasons (e.g. soil depth is increasing due to very effective conservation activities), a unit of soil loss results in declining reductions in yield, then declining rather than constant α_{ibi} values are used. Similarly an increasing elasticity relationship is attained by specifying increasing values of α_{ibi} in the model. Overall, the Lal yield decline model calibrated for the Ginchi watershed conditions and linked to a modified USLE model helps us bridge the gap in the amount of data required to carryout an analysis of this nature and magnitude. All that is required to be known (or estimated) is the annual rate of soil loss and the mean current yields. The model is then able to estimate current and future crop losses adjusted for the ameliorative effects of dung manure and artificial fertilizer application, slope and soil depth. Moreover, further accuracy of the model may be achieved by comparing model projected farm crop yield decline over time with the observed yield trends under continuous cultivation in areas with similar conditions to the site under consideration.

Ginchi area was found to have very sparse data on the relationship between rates of soil loss and decline of yields of cereals and legumes. Considerable reliance was hence put on key farmer interviews on yields obtained on individual plots of the major crops over the past years. This information was compared with experimental data from other parts of sub-Saharan Africa. More specifically, soil loss yield decline data from Kano, in Nigeria were used to validate farmer recall data for some of the crops. Based on this data set, penalty values (α_{ib}) were set in the range that resulted in the expected yield changes per unit of cumulative annual soil loss i.e. between -9.9 to 0.4% of annual yields for legumes, millet and sorghum (with and without dung manure) under continuous cultivation from clearing (Nye and Greenland, 1960).

3.2 Soil nutrient balances

Nutrient balances are compiled by equation (11) below:

$$NUTBAL_u = \sum_{b=1}^{4}\sum_{m=1}^{6}\left[\sum_{i=1}^{12}\sigma_{ui}.X_i + \sum_{h=1}^{2}\sigma_{uh}.X_h + \sum_{i=7,8,10}\nu_{ui}.X_i + W.\gamma_u + W.\psi_u\right] - \sum_{b=1}^{4}\left[\sum_{i=1}^{12}\partial_{iu}.Q_i + \sum_{h=1}^{2}\partial_{hu}.Q_h\right] - E.\omega_u - Leach$$

where

$NUTBAL_u$ = A vector of nutrient balances;
i = crop and pasture activities in the watershed;
b= denotes the four land types, m denotes seasons in the crop year, h are tree activities;
u= 1, 2 and 3 refers to major plant nutrients specified as nitrogen, phosphorous and potassium respectively;
σ_{ui} = amount of nutrient *u* applied on a unit (ha) of crop activity *i* through dung and chemical fertilizer use;
σ_{uh} = amount of nutrient *u* applied on a unit (ha) of type *h* tree activity through dung and chemical fertilizer use;
ν_{ui} = amount of nutrient *u* added to the soil by crop activity i e.g. nitrogen fixation;
W = Total watershed area in hectares;
Υ_u = per ha addition of nutrient *u* through atmospheric deposition;
ψ_u= Biological nitrogen fixation;
∂_{hu} = Amount of nutrient u contained in a unit of crop i harvests;
Q_I= Quantity of crop i harvests;
Q_h = Quantity of tree h harvests;
E = Aggregate amount of soil erosion generated in the watershed;
ω_u= Amount nutrient u in a unit of soil lost through erosion;
$Leach_u$ = Amount of nutrient u lost through leaching.

3.3 Validation of the economic component of the bio-economic model

Overall, the bio-economic model was implemented as an aggregate level dynamic non-linear programme with some resemblance to the one used by Moxey et al. (1995). The model treats the study area as a single profit maximizing farm, planning for a twelve year time horizon and choosing a land use mix constrained by existing static traditional technology on one hand and a set of new technologies on the other. No consideration is given to terminal values purposely, as a way of capturing the effect of some of the plots allocated to a farmer being redistributed to other farmers (Gryseels and Anderson,1983). The choice of a twelve year plan horizon was based on the length of time after which farmers thought such a land redistribution may occur. Again as noted above, this tended to be when some existing families required more land than previously allocated due to children coming of age, marrying and forming independent families. A 1995 survey of 64 households in the watershed showed that 13% of the households had lost some of their plots in this manner over the previous five years. The farm survey showed further that farmers tended to own fragmented farms i.e. plots of land scattered across the landscape. The model also attempts to simulate farmers' decision making processes by choosing a land use mix constrained by seasonal resource availability including substitutability of labour across gender. This is based on results of a characterization study carried out in 1994-95 that indicated a substantial transfer of labour across gender and crop activities among other findings. Based on this information, a structured questionnaire with gross margin tables dis-aggregated to reflect labour per ha by gender and other input use and the resulting yields for each season were used to collect information for generation of input-output coefficients for the various crops in the watershed. Policy restrictions, institutional arrangements and previous production choices were similarly endogenized. Spatial variation across the watershed is attained by the model choosing activities that are ecologically and economically suitable on each land type. Some agricultural activities unique to a specific land type are attached as production possibilities to that land class and not on others. Combining the economic model with the above soil erosion yield decline model enables simultaneous generation of optimal levels of soil erosion (nutrient losses) associated with each optimal income and land use pattern. This traces out the relationship between technology uptake and the impact on the watershed sustainability indicators such as cash income, food security and environmental degradation through soil loss and nutrient depletion.

Construction and validation of the economic component of the model is hence based on 1995 observed land use patterns displayed alongside model results, both for the static and dynamic models. Consumption habits that dictate the bias towards production of teff and wheat i.e. staples, on almost all the land types and especially on land type A and B were taken into account by specifying minimum area under teff and wheat in these two land types. Failure to do so would have resulted in a land allocation that does not reflect people's production and consumption preferences and also their attempt to be self sufficient in most of the grains and pulses. Owing to the large number of pulses, spices and oil crops grown on small plots of land; however, some aggregation of these activities was necessary. Thus area under fenugreek, horsebean, and noug were lumped together and were considered under the "other crop" category as suggested by Hazell and Norton (1986). Crops such as sorghum, and millet observed only on the slopes of land type D with limited possibility of cultivation on land type A, B and C were excluded from possible choices of land use in these land categories.

More details on production possibilities and profitability of activities included especially in the dynamic bio-economic model were also based on the Ginchi watershed characterization survey of 1990. This study was conducted by the JVP consortium of institutions between 1989 and 1990. Gross margin tables (i.e. crop budgets) for teff, wheat and chick pea, compiled from these 1990 watershed observations were used to cross check further the model input output (I-O) crop coefficients. Given that no multiple intervention had been made in 1995 and hence the impact of fertilizer and dung application had not been realized, validation of the multiple intervention version of the model was done based on crop budgets derived in areas with relatively high fertilizer and dung use and with considerable adoption of some of the BBM set of technologies that are scheduled to be introduced in the watershed. Only areas with environmental conditions similar to those in Ginchi watershed were considered in generating these coefficients using crop budgets for 1995 prepared by USAID (Unpublished data). Relevant adjustments were made to take into account the fact that labour is not costed in Ginchi as it is generated mainly from family members. They also had to be adjusted for the geographical price differences. More specifically, the most important information obtained from these gross margin tables were the per hectare input-output technical crop coefficients for human and animal labour use, per ha yields and per unit input use of seeds, chemical fertilizer and other chemical inputs.

Thus average yields obtained for local variety teff with fertilizer application rate of 65kg (DAP) per ha are 1300kg in West Gojam. These compare with model per ha yields of 2053, 2086, 1425, 1425 kgs/ha on land types A, B, C and D respectively when 60kgs/ha of DAP is applied. Given that Ginchi watershed is considered to be among the most fertile teff growing areas in Ethiopia and also taking into account the multiple impact of other technologies on yields, these figures are within the expected range. Likewise, values for traditional wheat yields of about 1750 kg per ha when fertilizer is applied at a rate of 80 kg in the Assella , Arsi zone compare favorably with estimates generated and used in the model that are in the range of 2480, 2390, 1425, 1868 kg per ha for land types A,B,C and D respectively assuming a fertilizer application rate of 90kg per ha.

3.4 Risk Considerations

With prevailing high variability in weather conditions in Ethiopia, modeling risk related to rainfall is obviously important. One way of doing this is to specify risk functions on the biophysical side of the model (i.e. effect of rainfall outcomes on yields). Modelling risk in the objective function which is generally straightforward (Hazell, 1998) may, hence, not be appropriate. The difficulty lies in the fact that bio-economic models incorporate many production and environment processes whose outcome each year are variable and are in turn shocked by risk events as well. Thus with variable rainfall, soil erosivity, rainfall and soil erodibility factors in the USLE model will no longer be deterministic as specified above. Similarly the soil loss-yield function will also be shock dependant (including the penalty parameter, α for each crop activity *i*). Capturing these shocks and specifying the ways in which farmers respond to them (i.e. adjusting input use coefficients, animal stocking rates for example) requires more complicated stochastic programming approaches. Such adjustment is likely to result in typically large models that are difficult and cumbersome to solve (Hazell 1998). For these reasons and also due to limited time series data on most of the relevant variables, risk is not explicitly considered in this model.

3.5 Sensitivity Analysis

Ginchi bio-economic model relies on a number of assumptions that are not easily verifiable. Estimated soil losses are an obvious instance and perhaps the most fundamental. An attempt to verify the projected erosion level was done on land type A in the watershed through a soil erosion measurement experiment. Erosion values were found to be in the range of 11 – 14 tons per ha (Michael Klaij, personal communication). These compared well with projected model estimates under the limited intervention scenario that were in the range of 13.5 to 15.4 tons per ha over the twelve year time horizon. Verifying the estimates of projected soil losses on the other three land types would require years of painstaking measurement in the field. However, since the model's projected estimates on one of the land categories is close to the observed values, the rest of the soil loss estimates on the other three land types are considered to be close to reality too.

Other components of the model, e.g. discount rate, input and output prices, are also susceptible to change. Their influence however is more readily checked. The impact of a high and low discount rate, for instance, on the model solution especially in the scenario simulating the current static traditional technology was tested. Results are displayed below

Sensitivity analysis of model economic and biophysical indicators to changes in discount rate

Discount rate	5%	12%	15%	25%	35%
Income in millions of birr	4.5	3.3	2.8	2.2	1.5
Soil erosion in '000 tons	102	102	102	104	105

This analysis indicates low sensitivity of erosion and high sensitivity of income to high discount rates. Thus the higher the discount rate the more the erosion but an even more loss of income, implying the tendency to prefer short term high paying erosive activities to less erosive but low paying activities. These results are consistent with conclusions drawn by Burt (1981) and Shiferaw and Holden (1998) who empirically show that high discount rates reduce uptake of soil conservation measures such as tree planting and hence support policies for poverty reduction on both efficiency and sustainability grounds. The same is true for investment in soil conservation activities in Ethiopia. There also exists a range of discount rates i.e. 5-15% that don't seem to have a significant impact on erosion. Similarly the impact on income of discount rates in the range between 15 and 25% could be small when compared to the extreme values of 5 and 35% respectively. A 12% market rate of discount is used in this model.

These results indicate the impact of interest rates on the biophysical and economic indicators of highland ecosystems. Sensitivity analyses for the situation after intervention whilst conceptually straightforward was extremely time consuming and therefore were not carried out. For similar reasons the individual effects of each technology are not assessed and instead all the technologies are assumed to be available for the farmer to choose the most viable ones.

4. MODEL RESULTS

4.1 1995 base model and its outcomes

The 1995 actual land use pattern and its outcomes are summarized in column 1 of Table 1 which also shows model projected land use patterns and outcomes for the intervention with multiple technologies scenario. These actual or observed values indicate a diversified land use pattern with a bias towards teff production and considerable dependence on the market for essential grains. This bias arises from the eating habits and secondly from the fact that teff prices tend to be 20% higher than wheat prices in the two local markets. More than half of land type A is put under teff production while the rest is shared among local wheat cultivation and other crops such as pulses and spices. The amount of land left for animal pasture on this land category during the wet (cropping) season is minimal, i.e. 7% of the total. On land type B, over 60% of the land is allocated to teff while pulses take 20%. The remaining 20 percent is shared among wheat, maize, hay making and pasture. Teff dominates land type C covering almost 50% of the area with maize being grown around the homesteads using dung manure. Pulses and wheat utilize most of the remaining land. Similarly, a significant amount of land type D (steep slopes) is used for teff cultivation with other crops and maize taking up half of the land.

Only about 19% of the watershed farmers planted the new wheat variety ET 13 in 1995. Most of them were observed to prefer cultivation of traditional wheat variety for a number of reasons ranging from easy availability of seeds and less fertilizer requirements to lower draught power requirement for tillage.

Land use pattern in the dry season and after crop harvest changes drastically. Most land is used for communal grazing by all the watershed dwellers. Thus animals belonging to farmers in the bottom parts of the watershed roam freely throughout the watershed to the steep slopes in land type D and vice versa. Moreover, animals from outside the watershed graze within it while watershed animals, similarly, graze outside the watershed boundary. It is assumed that these two transfers cancel each other out.

The above observed land use pattern had certain implications on farmers' level of cash income and nutrition. Total amount of grain and pulses generated were used for consumption while some were sold to provide modest cash income to meet household non-food needs. However, sale of crops during harvest time impacts negatively on the availability of food later in the year. From the survey results above, we note that it may have worsened the nutrition status of 40 % of the households that had already realized insufficient amounts of grain yields necessary to meet their daily food requirements. Thus substantial amounts of grains had to be bought in to meet shortfalls, averaging about 13 tons of teff and 7 tons of wheat during the cropping season and especially just before crops were harvested. Overall, farmer's daily consumption levels were low, estimated at 1500 calories per adult equivalent per day. Incomes generated by these crop sales are modest, estimated at 1200 birr per household per year.

The estimated level of soil loss arising from the observed land use pattern in the base year was 31 tons per ha per annum. This is about 26% lower than the national average for cropland (Hurni, 1987). Crop rotation and diversification as well as a modest amount of fertilizer application are currently the main practices used to reduce soil loss by enabling more prolific growth and hence better groundcover.

Maize and wheat are generally less erosive than teff and pulses due to their larger canopies and better rooting systems. Soil nutrient balances arising from this land management were calculated using the methodology specified earlier. Soil nutrient balances were estimated at –58kgs for nitrogen, -32kgs for phosphorous and –114kgs for potassium. Figure 1 shows the amount of soil loss and Figure 2 depicts the major contributors to the negative nutrient balances namely erosion, crop harvests (grain and straw) and emissions (leaching and gaseous losses). We note that soil erosion may account for more than a half of these losses while crop grain uptake could contribute about 14%. The rest may be lost through straw harvests for animal feed and/or through emissions. The values depicted in figure 2 support studies carried out elsewhere in the region. Thus Van den Bosch et al. (1998) attribute high loss of nutrients through soil erosion to the fact that "… fine particles are dislodged first in the process of erosion… hence eroded soils tend to be richer in nutrients than soil in situ" so one of the major factors leading to unsustainable agriculture in the sloping uplands is soil erosion.

4.2 Impact of land tenure policy with limited technology intervention

To capture the impact of land tenure policy on the natural resource base and specifically on nutrient balances, the base model was run, first with a short time horizon (1995-1998) and then with a long time horizon (1995-2006). The assumption was that farmers with insecure land use rights are likely to prefer short term plans to long term ones and vice versa. By comparing results of the four year and twelve year time horizon runs of the dynamic model (not shown in Table 1), it was possible to discern the differences in the effects of each type of planning horizon. An examination of model results of estimated soil losses at the end of 1998 (short time horizon) and in 2006 (long time horizon), revealed that soil losses in 1998 were likely to be 20% higher than in 2006. Surprisingly, income generated in 1998 was projected to be only 2.6% higher than in the year 2006. Insecure land policy thus appeared to create an income illusion that promoted land degradation. Given that nutrient loss through soil erosion accounts for over 50% of the total amounts of nutrients lost, it was apparent that an insecure land tenure policy was likely to aggravate the soil nutrient mining problem. Moreover, loss of nitrogen, phosphorous and potassium with very limited gains in income implies declining capacity of farmers to meet fertilizer application costs and hence incapacity to sustain current incomes over time. The 12 year model output thus showed that income increases under an insecure land policy are not likely to be sustainable.

There is hence a strong argument for soil conservation in the watershed if its sustainability in terms of crop nutrient availability (especially nitrogen and potassium) is to be maintained. The main conclusion from these baseline model values is that intervention is necessary to help quell the farmers problems of land fragmentation, waterlogging, inadequate diet and soil loss. Alignment of drainage channels across slopes and plots would require an improved Vertisol technology package involving communal action to construct a communal drain. Co-operation among land owning farmers through formation of rules and norms to be followed by the local community for governance of the use of crop land and private and communal pasture land would also be essential. Family labour and draught animal supply was envisaged as likely constraints to farmers' adoption of new crop, livestock and soil management technologies.

4.3 Multiple intervention scenario with current consumption level

Having examined the baseline situation, the next question was what was likely to happen when a package of technologies were availed and presumably adopted by the farmers and consumption patterns remained the same while limited population growth occurred over the planning period? Answering the question would require comparison of the net gains of a unit of nutrient conserved through adoption and use of a combination of land management technologies with the related costs of such adoption posed a major challenge to this study. In this regard, the bio-economic model was used to evaluate the tradeoff between efficiency gains from optimal site specific technology intervention based on land suitability (in terms of increased yields or reduced per unit input costs) and the associated costs of such intervention in terms of per unit input costs of the technology adopted. The optimization process ensures that only those technologies whose per unit marginal returns are above or equal to their associated per unit marginal costs are considered in each period. For each site for instance, the model calculates the optimal fertilizer and dung application rates for every crop activity and then selects the most viable ones for cultivation in a particular year based on their relative prices and costs. This represents a significant contribution over past studies (e.g. Smaling et al., 1996; Van dan Bosch et al., 1998; De Jaeger et al., 1998) that have been generally diagnostic in approach and therefore failed to consider interventions aimed at improving nutrient balances through land use patterns that are based on land suitability.

The technologies considered are:

a) construction of communal drain to eradicate water logging in the bottom lands,
b) use of a new high yielding wheat variety,
c) use of dung as manure instead of burning it for fuel,
d) planting of eucalyptus trees and harvesting them after every four years for sale as construction poles and as wood fuel
e) keeping the optimal number of livestock based on available feed, their commercial sales value and their capacity to generate dung manure for crops.

Existence of a good marketing infrastructure was assumed and consumption was assumed to be at the 1995 base year levels of 1500 calories per adult equivalent per day. An examination of model results reveals that a tenfold rise in cash incomes is possible and is likely to be accompanied by a 20% decline in soil loss when compared to 1995 observed base year values respectively (Table 1). There is also a likelihood of an increased reliance on farm output to meet the increasing demand for food over the years. The optimal number of animals, as projected by the model, at the beginning of the plan period (i.e. the base year), may however, be less than a third of the observed numbers in the watershed. These numbers are, nonetheless, projected to gradually rise over time with temporary drops coinciding with commercial sales of animals and culling of the old stock. Thus by the end of a 12 year planning horizon, livestock numbers may have risen by about 27% from the base year numbers.

Compared to actual observation in the watershed, these results compare favourably. Planting of eucalyptus for commercial purposes, for instance, has been shown to earn farmers more than ten times what they earn from crop cultivation. Similarly, cultivation of crops using chemical fertilizer and dung manure has resulted in linearly increasing yields and in some instances, yields have doubled or even tripled (Wrigley et al., 1969, in Mpairwe, 1998).

Table 1 displays the land use pattern for selected years as projected by the model. The years 1996, 1998, 2001 and 2006 are chosen for illustration purely because they represent fairly representative intervals. Examination of model estimated land use pattern on land type A indicates teff as the main activity occupying 37 % of the land from the first year right through to the seventh year. In the eighth year, model projected area under teff rises to 40% and then 47 % and 56% in the ninth and tenth years respectively. In the eleventh and twelfth years, teff area is likely to be as high as 65% of the land type A total crop land area respectively. Average model estimated area under teff on this land type over the twelve year period is hence 24 ha or 44% of this land type's crop area. This favourably compares with observed area under teff in 1995 of 26.65ha (or 49% of land category A arable land) leading to the conclusion that this land type has probably an increasing comparative advantage in teff production relative to other crops. The results hence closely resemble the observed land use pattern in the base year.

We also note that local traditional wheat variety is likely to be dominantly grown on land type A especially in the third to the fifth year, as the model output shows that it may be committed to 28% of land type A crop area. It is, however, likely to be substituted with the new wheat variety (cultivar ET 13) in some of the years as evidenced by its replacement with ET 13 wheat variety in the sixth year. Further examination of the model projections also shows that cultivation, of the traditional variety of wheat, nonetheless, resumes in the eighth year but under a declining land area. The area is projected to decline from 28% in 2002 to 8% in 2004 before cultivation eventually ceases in 2005. Again these model projected trends compare fairly well with actual observations in the base year. As reported in the baseline model above, cultivation of local wheat variety persists even when farmers have the option of utilizing new high yielding wheat variety. This is most likely due to the high labour demands for planting new wheat varieties (i.e. ET 13 cultivar) which are observed to be 24% higher than those of local wheat variety. Note also that cultivation of new wheat varieties in land type A requires a fairly thorough ploughing, making of furrows with the BBM plough and construction of the communal and feeder drains for improved drainage as well as purchase and use of certified seeds and fertilizer. It is hence also likely that though yields of ET 13 are obviously higher than those of local wheat variety, the high labour requirements especially for male labour conflicts with the high labour demand for teff, which, as we have observed, is the most preferred staple in the watershed. The relatively low labour demand during peak labour periods (i.e. land preparation, planting, and harvesting) of growing traditional wheat variety hence enables the farmer to have fairly adequate time to cultivate and manage the highly labour intensive teff and especially during such peak seasons. These may be some of the reasons contributing to the attractiveness of cultivating local wheat variety as opposed to new wheat variety. Moreover, yields of the new wheat variety are highly variable across farms as evidenced by on-farm experiments carried out in the watershed by the Ethiopian Agricultural Research Organization. They range between 0.54 to 1.9 tons per ha. However, the advantage of cultivating local wheat varieties is likely to diminish over the years as the negative effects of soil erosion increase cumulatively over the years and therefore require more and more fertilizer applications on wheat varieties that have a better response to fertilizer use such as cultivar ET 13.

4.4 Multiple intervention with recommended consumption

Recommended consumption for Ethiopia is about 2000 calories per adult equivalent per day. The implication of the multiple technology intervention for achieving the higher consumption level is examined by comparing three scenarios : soil losses when fertilizer is the only intervention in the watershed, soil losses with multiple intervention and 1500 calorie consumption per adult equivalent per day, and soil losses when multiple intervention is assumed to occur under recommended consumption levels of 2000 calories per adult equivalent per day. The loss levels for the three scenarios are presented as pink, blue and green lines respectively in Figure 2. Quantities of chemical fertilizer used on the major crops to achieve the own production subsistence targets at the recommended levels of 2000 calorie per adult equivalent per day are displayed as bar charts on this graph. They thus reflect the associated input costs as well as nutrient inflows of the multiple intervention scenario generating soil loss when consumption at recommended levels of at least 2000 calories per adult equivalent is assumed. Likewise, in order to see the possible soil nutrient balances arising from consumption at recommended calorie intake levels, nutrient balances calculated by equation 11 above are displayed at the bottom part of figure 3.

Detailed results are presented in Okumu et al. (1999) and Okumu (2000). Summary results shown in Figure 3 indicate that with multiple technological and policy intervention and consumption targets at 2000 calories per adult equivalent per day, soil losses are likely to be higher than those generated under multiple intervention situation with a minimum calorie intake of 1500 per adult equivalent per day. With limited intervention and a similar calorie intake of 1500, soil loss levels may be the highest. We may, therefore, conclude that when the set of multiple technologies are combined with conducive policy environments such as a secure land policy, the result could be a forward shift of the watershed production possibility frontier that could enable higher outputs at lesser biophysical and economic costs than before. The extent of this shift may however be reduced if self-sufficiency in food production for consumption at recommended levels is emphasized by farmers as a goal. Dependence on the market to meet some of the household food supplies, therefore, impacts positively on the sustainability of the watershed by enabling the use of land based on land suitability and flow of outputs from surplus households to deficit ones through exchange. It also allows benefits related to the law of comparative advantage and the related economies of scale to be realized.

In terms of input allocation, examination of the amounts of fertilizer used to attain own production subsistence consumption of 2000 calories per day per AE shows a bias towards application of fertilizer on teff and wheat. A substantial amount of operating capital must hence be spent on these crops to attain the set consumption goal over time. Given the negative effect of soil erosion on yields and hence income and nutrition, there has to be a definite effort in some of the years to lay off land as a means of reducing soil loss (Okumu, 2000). However, such fallowing, may only be possible where purchases and sales from the market are options and cash income generated from on farm activities is substantial. This may only happen under an intensification strategy that increases productivity and generates adequate surplus for the market from a reduced crop land area. Not only does this apply to Ginchi area but is also applicable to similar areas throughout the highland ecosystems of similar conditions.

5. CONCLUSIONS AND POLICY IMPLICATIONS

The bioeconomic model, because of its very nature, and disaggregation of the watershed into relatively homogenous land types allows application of traditional techniques such as the USLE in a dynamic mathematical programming framework to asses socioeconomic and environmental impacts of technology and policy interventions in an integrated manner. Model results with different technology and policy scenarios indicate considerable tradeoff in terms of environmental and socio-economic goals. In terms of nutrient balances, model estimates show an obvious correlation between soil nutrient balances and soil erosion in the watershed. Some nutrients, however, show a higher correlation than others. Nitrogen, for instance shows less correlation with soil erosion especially in the last 5 years of the planning horizon. This signifies an attempt to use inflows (dung and chemical fertilizer) to replace losses arising from soil erosion and crop harvests. Phosphorous shows a slightly higher positive relationship with erosion but its values are less pronounced due to the smaller absolute values and the ameliorative impacts of DAP fertilizer application used mainly to replenish nitrogen. Potassium balances depict a strong and direct positive relationship with erosion quantities. The higher the erosion the higher the amount of potassium lost per ha. This is not surprising given that dung manure is the only source of potassium inflow (imports).

Under the multiple intervention scenario, we note that there is a positive relationship between soil loss and nutrient depletion (i.e. decline in soil loss results in decline in nutrient loss), a negative relationship between soil loss and human nutrition (increase in soil loss results in increase in human nutrition) and a positive relationship between human nutrition and fertilizer use or costs. We however observe that intervention with multiple technologies and policies reduces the magnitude of these relationships.

From a policy standpoint, it is clear that well targeted policies that provide incentive to use land according to suitability and the comparative advantages of these land categories can enhance overall social welfare be increasing income as well as conserving resources or at least by reducing degradation. Emphasis may be on policies that promote both short term and long term activities and give room for gradual adoption of improved recommended technologies. The dichotomy between private and communal actions must be recognized and appropriate policy environment created with a view to increasing the effectiveness of each. Care should, however, be taken to avoid promotion of conflicting policies. Preferably, those technologies that have multiple impacts in terms of meeting both the human welfare and biophysical objectives must be prioritized and appropriate policy instruments enacted to facilitate the same.

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Figure 1: Estimated Nutrient outflows in Ginchi Watershed

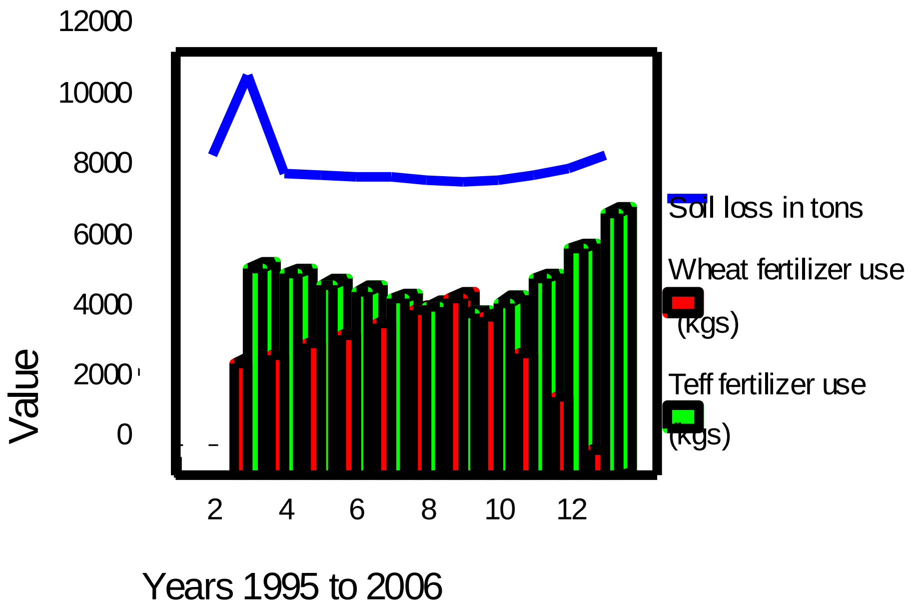

Figure 2: Estimated Nutrient outflows in Ginchi Watershed

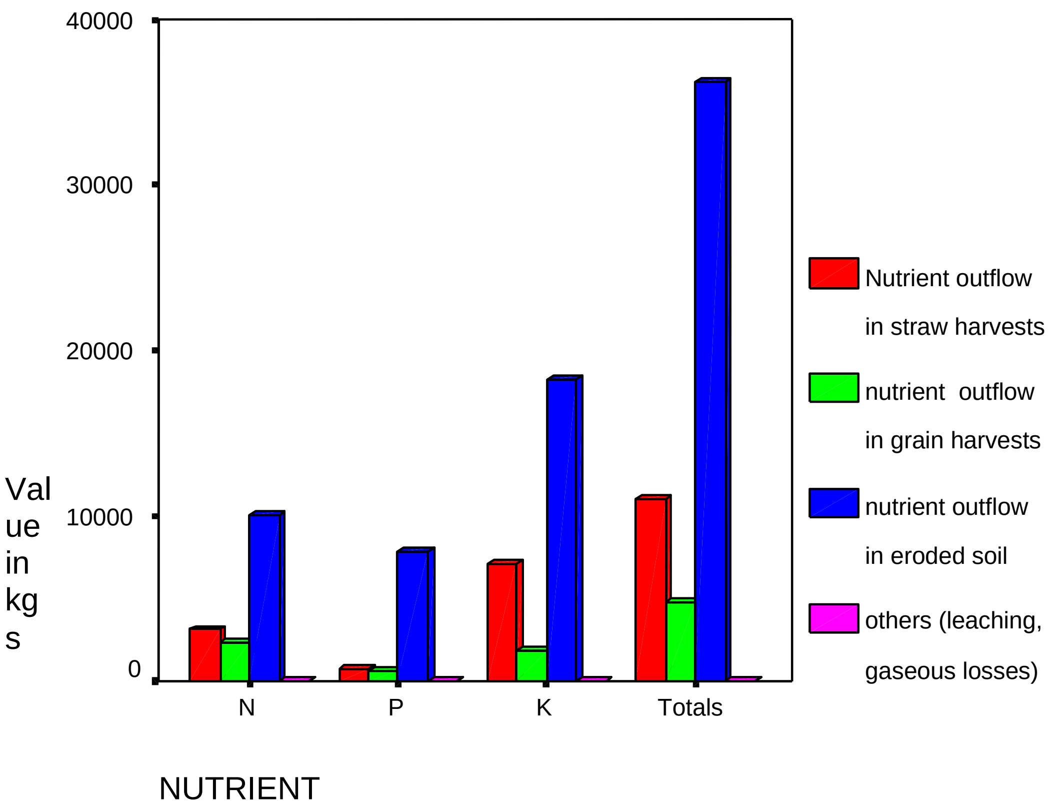

Table 1. Actual and estimated values of land use (ha), income (birr) and erosion (t/ha) of the dynamic version of the model with multiple intervention and consumption at 1500calories/ AE/ day

Type of activity	*1995 actual values*	Twelve year time horizon Model estimated values			
		1996	1998	2001	2006
Prodn. (by landtype)					
Eucalyptus A	-	-	-	-	-
Teff A	26.65	20.00	20.00	20	35.00
Wheat A	10.38	15.00	15.00	15	-
Others A	12.80	5.00	5.00	5.00	5.00
Hay A	-	13.00	13.00	13.00	13.00
Grazing A1	3.12	-	-	-	-
Grazing A2	54.00	54.00	54.00	54.00	54.00
Eucalyptus B	-	-	16.98	45.55	45.55
Teff B	67.71	40.00	40.00	40.00	44.33
Wheat B	9.86	-	-	-	6.79
Maize B	1.47	3.53	-	-	-
Others B	20.96	56.46	43.02	14.45	3.32
Hay B	6.50	15.00	15.00	15.00	15.00
Grazing B1	8.5	-	-	-	-
Grazing B2	105	105.00	88.02	69.45	69.45
Eucalyptus C	-	-	-	-	-
Teff C	15.31	-	1	-	-
Wheat C	7.67	1	-	-	-
Maize C	1.00	27.99	27.99	20.00	20.00
Others C	6.02	2.00	2.00	7.82	9.99
Hay C	2.50	7.50	7.5	7.50	7.50
Grazing C1	7.50	-	-	-	-
Grazing C2	25.50	25.50	25.50	25.5	25.5
Eucalyptus D	-	30	30	35	35
Teff D	16.15	-	-	-	5
Wheat D	2.30	-	-	-	-
Maize D	5.77	10	10	5	-
Others D	15.78	-	-	-	-
Hay D	7.30	12.50	12.50	12.5	12.50
Grazing D1	5.00	-	-	-	-
Grazing D2	54.00	22.50	22.50	19.50	19.50
Net Teff Buying (kg)	12,701	-53898	-31292	-7070	-4450
Net Wheat Buying kg)	7,106	-28720	-28338	-28338	-613
CASH INCOME (Birr)	149,397	2,510,695	3,553,788	2,483,182	4929208
Erosion (t/ha/yr)	31.0	24.33	23.34	19.74	21.28

Note: US$1=7 Birr

Figure 3: Interactions among fertilizer, erosion, consumption and nutrient mining