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 show that, without technological and policy intervention, soil nutrient balances, income and nutrition could not be substantially or sustainably improved in a highland area of Ethiopia. Although cash incomes could rise from a very low base by more than 50% over a twelve-year planning period, average per ha nutrient balances indicate significant nutrient mining and associated soil losses of about 31 tons per ha. With the adoption of an integrated package of new technologies (involving new high yielding crop varieties, agro-forestry, animal manure and inorganic fertilizers use, construction of a communal drain to reduce water logging and some limited land user rights), results show the possibility of a two-and-a-half-fold increase in cash incomes on the average and a 28% decline in aggregate erosion levels over a twelve year period given a population growth rate of 2.3%. Moreover, a minimum daily calorie intake of 2000 per adult equivalent could be met from on-farm production and per ha nutrient balances, while still negative for nitrogen and potassium, could be reduced by 36 and 6 % respectively, with phosphorous balances being reversed to positive values. However, these gains might be eroded by the need to meet increased nutritional demands arising both from increasing consumption levels and a more rapid population growth of over 2.8%. From a policy perspective, this reduction in nutrient losses in the face of higher reliance on the watershed for subsistence food requirements, would imply an increasing need for a more secure land tenure policy than currently prevailing, provision of credit to facilitate uptake of the new technology package and a shift from the current livestock management strategy that emphasizes use of livestock as a store of wealth to the one that encourages livestock keeping as a commercial activity. It would also imply a shift from a general approach to land management to a relatively more site-specific approach that recognizes the need for spatial and inter-temporal variability in input use based on land quality that would encompass an efficient nutrient management strategy.

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

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 outcomes and soil nutrient balance changes as these problems are targeted by specific technology interventions. The analysis proceeds using a bio-economic model applied at watershed level, (rather than a purely economic/ bio-physical model applied at farm-

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household level). The model is validated for the Ginchi watershed in the central highlands of Ethiopia. The current situation, involving limited intervention in the watershed, is compared with a situation involving integrated interventions. Our approach is motivated by arguments for a shift in focus from increasing agricultural production by use of purchased inputs to overcome soil nutrient constraints, 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 into the effects of proposed interventions on the gains and losses of major nutrients in the watershed and accompanying economic performance. This study aims at identifying effective and robust strategies for raising watershed income and improving soil nutrient balance, so as to enhance livestock and crop productivity over time in a typical tropical highland watershed such as the Ginchi area.

A dynamic non-linear mathematical programming model maximizes aggregate watershed financial surplus from agricultural production that is linked to biophysical aspects of the watershed through an exponential soil loss-crop yield decline model, with a single year time lag. Cumulative soil losses are computed for each year and these determine crop yields in the following year after accounting for the effects of chemical fertilizer and dung manure applications. The model takes into account seasonality in input requirements and outputs, labour substitutability, the various roles of gender, crop and livestock constraints, rising household food requirements, and forestry activities, as well as the biophysical aspects of soil erosion and soil nutrient balances arising from these activities.

Cross-sectional socio-economic and biophysical data from four land categories in the watershed for the years 1995, 1996 and 1997 are used to test the model and are supplemented with 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 components on one hand, and biophysical and human factors on the other.

Part two of the paper gives a background to 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). Since agricultural productivity is low, the 80% of population employed in this sector generates less than 50% of the GDP, and these low productivity levels continue to decline due to land degradation. Current estimated soil loss from cropped areas is 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).

The Ginchi watershed typifies the degradation problem in the Ethiopian highlands and similar highlands elsewhere. Located in the central highland massif, this watershed has experienced significant degradation over time. Evidence shows that in 1950, only 34% of the watershed was under crops while 60% was under pasture and woodland. The remaining 6% was under communal roads 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. These changes have been accompanied by increased severe erosion and drastic declines in crop yields and animal productivity. The bottomlands of the watershed also suffer from waterlogging at the beginning of the rainy season due to the predominantly clay 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 an integrated package of production and conservation technologies. The package includes improved animal drawn equipment for drainage (the Broad Bed and Furrow Maker or BBM), new crop/forage varieties and related agronomic practices, new breeds of livestock, 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, leads to higher demand for animal draught power for cultivation. Its success would depend on construction of drainage channels to drain off excess water from the individual farm plots to a communal drain or to the river channel. 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 resources. 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 currently available, putting pressure on the existing pastures. This study examines the potential implications of adopting this package of technologies.

3. ANALYTICAL MODEL

To date, most studies of the impact of technology on 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. It also avoids consideration of resource multi-functionality and the multi-dimensional trade-offs that emerge from this, as well as the important role 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. Thus, the analysis of the problem at an aggregate watershed level is viewed as more appropriate than individual household level analysis.

Watershed-level dynamic bio-economic models present a feasible method for implementing this watershed-level approach in the present case. In some circumstances, they may suffer from aggregation problems associated with averaging resource availability and other structural parameters across individual units (Hazell, 1998). Such problems arise where there is a mis-match between the form in which resources are available and the decision unit for allocation of these resources. In such cases the model may assume a degree of homogeneity in resource availability and flexibility in resource allocation that may not be reflected in the processes being modeled. In the Ginchi watershed, the likelihood of this type of problem is minimized by the high degree of homogeneity within the community in terms of quantity and quality of resource endowment especially land. As Gryseels et al. (1983) noted: " Membership in the Peasant Association[2] 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.". In addition, high inter-household interactions in terms of communal labour and animal draft sharing is observed, further increasing homogeneity of access to resources

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[2] Peasant Associations are government administrative units at village level headed by a council of village elders and comprised mainly of farmers living in the area.

and flexibility in use, hence justifying the assumption of a single decision maker at the watershed level. Population growth is modeled by assuming a corresponding annual increase in the demand for basic nutritional needs in the watershed.

3.1 The bio-economic model

The dynamic bio-economic model used here is focused on maximizing the margin over variable costs generated by agricultural activities in the watershed. Because of particular characteristics of the social and cultural framework in the Ginchi area this may actually be interpreted as maximizing aggregate utility based on income, leisure and basic food requirements[3] since it becomes possible to treat leisure and calorie intake as fixed and separable from income[4] in the utility function. Risk[5] is not incorporated due to limited time series data and the large size of the model.

The simplified model is specified as follows:

$$Maximize \quad \sum_{t=1}^{T} \frac{1}{(1+\tau)^t} \left\{ \sum_{i=1}^{p} \left[P_{it}Q_{it} - \sum_{c=1}^{r} P_{ct}X_{cit} \right] \right\} \qquad (1)$$

$$subject\ to: \sum_{i=1}^{p} a_{cit}Q_{it} \le \overline{X}_{ct} \cdots\cdots c = 1\ldots r \qquad (2)$$

$$Q_{it} \ge 0 \cdots\cdots\cdots\cdots\cdots\cdot i = 1\ldots p \qquad (3)$$

$$Q_{it} = \sum_{b=1}^{4} q_{ibt}h_{ibt} \cdots\cdots i = 1\ldots m \qquad (4)$$

$$\sum_{i=1}^{p} h_{ibt} \le W_b \cdots\cdots b = 1\ldots 4\ all\ t \qquad (5)$$

$$q_{ibt} = \phi\left(X_{1it}\ldots X_{rit}\right)e^{-\alpha_{ib}\beta_{bt-1}} \qquad (6)$$

$$\beta_{bt-1} = \sum_{k=1}^{t-1} \left({E_{bk}}\big/{W_b} \right) \qquad (7)$$

$$E_{bt} = \sum_{i=1}^{j} K_{ibt}N_{ibt}R_tD_tZ_tS_t \qquad (8)$$

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[3] In the model, food requirements are assumed to be determined by increases in the size of population over time and its composition, and are constrained to levels that ensure a minimum daily calorie intake per adult equivalent. Both calorie intake and a teff and wheat grain minimum consumption requirement are set to progressively increase over the planning horizon to cater for population growth in the watershed.

[4] It may also be assumed that leisure and income decisions are strongly separable. In the 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 used for farm work. Leisure is thus a component of the church holidays and can be assumed fixed. Holding church holidays constant leaves income as the only argument of the utility function.

[5] 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 an optimization behavior.

where:
b refers to land type (=A, B, C or D),
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 activities,
Q_{it} is the quantity of output produced by activity i in time period t,
P_{it} is the price of output produced by activity i in time period t,
X_{cit} is the quantity of input c used by activity i in time period t,
P_{ct} is the price of input c in time period t,
$\overline{X}_{ct}$ is the total quantity of input c available in time period t,
τ is the discount rate,
a_{cit} are the technical coefficients of production,
q_{ibt} is 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 base,
α_{ib} are crop specific coefficients varying with land use activity i and land type b (i.e. slope, soil type and depth),
E_{bt} is soil loss from land type b in period t,
β_{bt-1} is the cumulative soil loss in tons per ha for the preceding t-1 years on land type b, and
W_b is the area of type b soils in hectares in the watershed.
K_{ibt}, N_{ibt}, R_t, D_t, Z_t and S_t are coefficients in the Universal Soil Loss Equation.

Cumulative soil loss is calculated by summing over past years' E_{bt} values. These are annual soil losses estimated by the Universal Soil Loss Equation (USLE) Model. E_{bt} is thus the level of erosion on land class b while W_b is the area of type b in hectares in the watershed; K_{ibt} is the land cover by activity i on land class b; N_{ibt} is the management of activity i on land class 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. Land type A is comprised of Vertisols of 0-4% slope, land type B Vertisols of 5-9% slope, land type C alfisols of 10-15% slope while land type D is comprised of acrisols of over 20% slope. One potential problem with using the USLE in the current context arises from the fact that this model is designed for estimation of gross soil loss from individual homogenous tracts of land, rather than net soil loss from a series of interconnected plots. Thus it is not designed to measure soil deposition occurring in a watershed as soil eroded from one land type is deposited on a land type at lower altitude. However this problem does not arise in the current context because each tract of land was observed to slope towards a riverine, so that most of the eroded soil is deposited in the water channels and carried away by the river rather than being transferred to another land type within the watershed. Thus, gross soil loss on each land type is approximately equal to net soil loss.

The model utilizes a dynamic mathematical programming procedure to adjust yields each year over the planning horizon as a function of cumulative soil loss in previous years using equation (6). This is a modified version of the model developed by Lal (1981) and used by Ehui et al., (1990) and Bishop (1995). The function $\phi(.)$ refers to yields without soil erosion, taking into account crop management practices, application of dung and artificial fertilizer use. Then $e^{-\alpha_{ib}\beta_{bt-i}}$ expresses the decline in yields due to cumulative soil loss effects. The parameters of this relationship have been estimated by Lal (1981), who used a regression approach to estimate equations for eight crops and four slopes (1, 5, 10, 15%) of alfisol soils in Nigeria. The estimated values for (α) ranged between 0.002 and 0.036 for legumes and 0.003 and 0.017 for cereals. All except one of the alpha coefficients were significant at 5% level.

For Ethiopian conditions, particularly the Ginchi study area, no experimental studies had been carried out to estimate yield decline due to soil loss on the various slopes of the watershed. However, conditions on the Nigerian site are similar to those in Ginchi in terms of soil erodibility and erosive climatic regime. 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. The model is further modified to take into account the fact that crop yields are not equally sensitive to soil loss across all soil types and slope. Based on expert judgement and intuition, the coefficient α_{ib} is varied by crop type, 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_{ib} is varied to capture the yield decline differential due to these factors. The range of coefficients used lie within the range of those derived by Lal (1981) for broad categories of crops such as legumes and cereals.

The Lal model, calibrated for the Ginchi watershed conditions and linked to a modified USLE model, helps bridge the gap in the amount of data required for this analysis. Given an estimate of the annual rate of soil loss and the mean current yields, the model is able to estimate current and future yield losses adjusted to account for the effects of dung manure and artificial fertilizer application, slope and soil depth. Further validation of the model is achieved by comparing model projected crop yield decline over time with observed yield trends in areas with similar conditions to the Ginchi site.

Additional data on the relationship between rates of soil loss and decline of yields for cereals and legumes in the Ginchi area, was obtained from key farmer interviews about yields obtained on individual plots of the major crops over past years. This information was compared with experimental data from other parts of sub-Saharan Africa. More specifically, data on soil loss and yield decline from Kano, Nigeria was used to validate farmer recall data for some of the crops. Based on this data set, the model used in this study generated expected yield changes per unit of cumulative soil loss of between -9.9 to -0.4% of annual yields for legumes, millet and sorghum (with and without dung manure). This scale of yield change is consistent with what has been previously observed under continuous cultivation (Nye and Greenland, 1960).

3.2 Soil nutrient balances

Nutrient balances are computed using the following equation:

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

$$-\sum_{b=1}^{4}\left[\sum_{i=1}^{12}\partial_{iu}.Q_i + \sum_{h=1}^{2}\partial_{hu}.Q_h\right] - E.\omega_u - Leach_u$$

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= Background 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 of nutrient u in a unit of soil lost through erosion;

$Leach_u$ = Amount of nutrient u lost through leaching.

3.3 Validation and sensitivity analysis

The bio-economic model was implemented as an aggregate level dynamic non-linear programme similar in some ways to the model used by Moxey et al. (1995). The model treats the study area as a single profit maximizing unit, planning for a twelve year time horizon and choosing a land use mix constrained by existing traditional technology on one hand and a set of new technologies on the other. The impact of limited tenure, arising from the way in which Peasant Associations reallocate land between farmers[6] (Gryseels and Anderson, 1983), is taken into account in setting the length of planning horizon. The choice of a twelve-year horizon is based on the length of time period after which farmers thought land re-distribution might occur. In addition, the lack of longer-term commitment that this system entails, is taken into account in the model by omitting from consideration the terminal value of livestock, crops, trees and land.

The model attempts to simulate farmers' decision-making processes by choosing a land use mix constrained by seasonal resource availability, including substitutability of labour by gender. This component of the model 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. A structured questionnaire, with detailed resource use budgets to reflect labour (by gender) per ha, other input use, and the resulting yields for each season, was then used to collect information on input-output coefficients for the various crops in the watershed. Policy restrictions, institutional arrangements and previous production choices are also taken into account. Spatial variation across the watershed is reflected in the model through inclusion of agricultural activities as part of the decision set for a specific land type and not others.

Construction and validation of the economic component of the model is based on 1995 observed land use patterns. Consumption habits, that dictate a bias towards production of teff and wheat staples especially on land types A and B, were taken into account by specifying minimum areas under teff and wheat on these two land types. Omitting these

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[6] Some of the plots allocated to a farmer may be redistributed to other farmers. 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.

restrictions would have resulted in a land allocation that does not reflect either the people's production and consumption preferences, or their attempt to be self sufficient in most of the grains and pulses. Because of the large number of pulses, spices and oil crops grown on small plots of land, some aggregation of these activities was necessary. Thus areas under fenugreek, horsebean, and noug were lumped together, and were considered under the "other crops" 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 not included in the options available for these latter land categories.

Additional details on production possibilities and profitability of activities included in the dynamic bio-economic model were 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 and detailed resource use budgets for teff, wheat and chick pea, compiled from these 1990 observations were used to cross check the model input-output (I-O) crop coefficients. No integrated intervention had been undertaken on or before 1995, and hence the impact of fertilizer and dung application had minimal impact in the watershed. Validation of the integrated intervention version of the model was therefore based on crop budgets relating to areas outside the watershed that had relatively high fertilizer and dung use plus considerable adoption of some of the BBM set of technologies. 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 differences in labor costs and prices.

Average yields obtained for the local variety of teff, with a fertilizer application rate of 65kg Di-Ammonium Phosphate (DAP) per ha, are 1300kg in West Gojam. These compare with model yields of 2053, 2086, 1425, and 1425 kgs/ha on land types A, B, C and D respectively, when 60kgs/ha of DAP is applied. Given that the 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, are consistent with estimates generated and used in the model that are in the range of 2480, 2390, 1425, and 1868 kg per ha for land types A, B, C and D respectively, assuming a fertilizer application rate of 90kg per ha.

Soil losses projected by the model for land type A were compared to the results of a soil erosion measurement experiment. Erosion values were found to be in the range of 11 – 14 tons per ha (Michael Klaij, personal communication). Projected model estimates under a limited intervention scenario were in the range of 13.5 to 15.4 tons per ha over the twelve-year horizon. Validating projected soil losses on the other three land types was not feasible within the time-scale and resources of this study. An investigation of the sensitivity of the results to the level of discount rate indicated that the principal economic and biophysical outcomes were largely insensitive to variations in the discount rate parameter within a wide range (5% - 25%) encompassing most feasible values. The results reported here are based on using a discount rate of 12%.

4. MODEL RESULTS

4.1 Actual Land Use Patterns

The 1995 actual land use pattern and its implications for producer incomes, trade in staple crops, and soil erosion are summarized in column 1 of Table 1. The 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 local eating habits and 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 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 at 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 the traditional wheat variety for a number of reasons, including easy availability of seeds and lower fertilizer requirements, as well as lower draught power requirement for tillage.

The land use pattern in the dry season, after the 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 of 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.

Overall, daily consumption was estimated at 1500 calories per adult equivalent per day, with estimated average household income of 1200 birr (US$120) per year. In addition to the grains and pulses produced in the watershed, substantial amounts of grains had to be bought in, amounting to about 13 tons of teff and 7 tons of wheat during the cropping season across the watershed.

The estimated level of soil loss arising from the observed land use pattern in 1995 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 were the main practices used to reduce soil loss by enabling more prolific growth and hence better groundcover.

Soil nutrient balances arising from this land management were calculated using the methodology specified earlier. Estimates per hectare were –112kg , -5kg and -63 kg of N,P and K respectively. These are in the range of reported losses for other sites with similar conditions in the Eastern African highlands. In the highly populated Kisii District in the Kenya highlands for example, the values stand at -112kg N, -3kg P and –70 kg K per ha per year (Smaling et al., 1993). Figure 1 illustrates the relative importance of the main factors contributing to these negative balances (soil erosion, grain and straw harvests and leaching/gaseous emission losses), showing 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. These values support studies carried out elsewhere in the region; for example 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".

4.2 The Baseline Scenario

As a starting point, a baseline version of the bio-economic model is run with population and consumption levels set at observed 1995 levels and with existing technology plus some inorganic fertilizer use. This model is used to simulate agricultural activities in the watershed over a 12-year time horizon. Population growth is assumed to occur at the current national average annual rate of 2.3% over this period. It is also assumed that livestock numbers remain static reflecting traditional practices of keeping more oxen than cows for plowing purposes. The resulting levels of agricultural activity, grain purchase, income and soil erosion from this scenario, for selected years over the twelve-year horizon, are shown in the second and subsequent columns of Table 1. Figure 2 provides an illustration of some key results in comparison with the patterns observed in 1995. By providing an estimate of how the system might evolve in the absence of integrated intervention and as population grows, these results provide a baseline against which the impact and robustness of integrated technology adoption can be judged.

Compared to the land use observed in 1995, a smaller area is devoted to teff and wheat by approximately 50 per cent and there is a shift in the cultivation of these crops from land types C and D to land types A and B. These differences reflect the increased yields that are made possible by limited fertilizer applications (allowing nutritional needs to be met from a reduced area) and the desirability of reducing the area devoted to more erosive crops[7] (teff) on land susceptible to erosion (land types C and D). There is a corresponding increase in area devoted to maize production on land types C and D.

The trajectory of grain purchases/sales and of farm incomes deserves special attention. The switch from the significant grain purchases observed in 1995 to substantial sales, predicted in year II and subsequent years in the baseline simulation, reveals the un-tapped potential from a more collective form of management without adopting the full package of technology – merely increasing fertilizer use. The significant decline in sales towards the end of the simulated period reflects the increasing difficulty of maintaining these yields (and of supporting the growing nutritional requirements) as cumulative soil erosion effects begin to have an impact.

It is also important to note that although area under some crops remains the same on some land types throughout the 12-year period, fertilizer application rates change across the years. For instance area under teff on land type B is constant at 40 ha each year. In year 2, however, an average fertilizer application rate of just under 50kg/ha is used, but by year 4 this has increased to 60Kg/ ha. Similarly on land type A, fertilizer application rates on teff are about 30kg/ha in the initial years but by the seventh year they have increased to 60kg/ha. Hence although the spatial dimension of the crop activity remains fairly constant, the net nutrient flows that define degradation intensify over time. On the other hand, the upper slopes (land type D) experience less

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[7] Maize, barley and sorghum are generally less erosive than teff and pulses due to their larger canopies and better rooting system.

variation in fertilizer input use rates per ha and more spatial changes in land use over time. Model results show that as time progresses, an increasing amount of wheat cultivation is undertaken on land type D between the second and the seventh year, replacing the less erosive maize, barley and sorghum. The result is a higher erosion rate that impacts negatively on wheat yields making its cultivation on this part of the watershed increasingly unsustainable. The land is hence reverted back to its former use (sorghum and barley cropping) by the eleventh and the twelfth year[8].

The combined effect of this trajectory of land use, grain sales and fertilizer use, would be an initial substantial boost in incomes that gradually erodes to levels at the end of the simulation period that are just less than 40 per cent of those observed in 1995. As an estimate of how the system might evolve in the absence of exogenous changes and as population grows, these results suggest that a "minimal change" strategy is not sustainable. As yields decline due to the cumulative impact of soil erosion even modest levels of nutrition cannot be sustained in the face of current levels of population growth.

Projected nutrient balances under this farming system, assuming modest fertilizer use on the part of watershed farmers, are -102kg N, -4 kg P and –65kg K. These compare very closely with the balances computed for the observed cropping pattern above. Thus the optimizing behaviour results in nutrient loss reductions of 8 and 25% for N and P respectively but a 3% rise in potassium losses. This scenario assumes no dung manure[9] use on the major crops, consistent with the observation that dung is usually burned as domestic fuel by households in the watershed. The nutrient results for this simulated base scenario are depicted in Figure 3.

Against this baseline, two scenarios are run to explore the possible impact of a package of new technologies (the JVP technologies), exploring the extent to which such a package might be used to alleviate the problems highlighted in the baseline scenario and how they might respond to the additional tensions generated by the increasing demands arising from the need to support increased nutritional standards and higher levels of population growth.

4.3 Adoption and Impact of the JVP Technologies

Evaluating the net gains achievable through adoption and use of the JVP technologies and related land management strategies, with the concomitant costs of such adoption, is undertaken using the bio-economic model. This model evaluates the net gains from optimal technology intervention based on land suitability. For each land type, for instance, the model calculates the optimal fertilizer and dung application rates for every crop activity and then selects the most viable for cultivation in a particular year based on relative prices and costs and taking into account the impact of cumulative soil erosion on yields. This represents a significant advantage over past studies (e.g. Smaling et al., 1996; Van dan Bosch et al., 1998; De Jaeger et al., 1998), which have been generally diagnostic in approach and did not consider interventions aimed at improving nutrient balances through optimally adjusted land use patterns.

The technologies that are part of the integrated package considered are:

a) construction of a communal drain to eradicate water logging in the bottom lands,

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[8] This can be interpreted as providing evidence of a type of crop rotation on the upper slopes.

[9] An additional run of the model, that allowed optimal adjustment of livestock numbers and modest use of dung manure, increased incomes by around 36 per cent. Though there was an impact on nutrient flows through increased recycling, this strategy had minimal impact on land use and soil erosion, hence failed to address the main source of nutrient losses.

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.

It is assumed that all these technologies are simultaneously available to farmers in the watershed. Existence of a good marketing infrastructure was similarly assumed, and consumption in all twelve years was set above baseline levels at 2000 calories[10] per adult equivalent per day; annual population growth remained at 2.3%. By increasing the nutritional demands on the system in this way it is intended to test the robustness as well as the effectiveness of the technology package.

The key model results for this scenario (detailed in Table 2 and illustrated in Figure 4) suggest that cash income can rise by more than 40% over that achievable in the baseline scenario (Table 1) representing an approximate two-and-a-half-fold increase over incomes observed in the watershed in 1995. This is accompanied by a decline of 28% in soil loss representing a reduction of just over 55% on observed 1995 levels. At the same time, average grain sales over the planning horizon decline substantially to around 44% of those in the baseline scenario. The optimal number of animals in the watershed also changes, cows increasing by around 6 fold and oxen declining to about one third of baseline levels, leading to an approximate doubling of total livestock numbers. These results are illustrated in Figure 4 in comparison with the baseline scenario.

The land use patterns underlying these results are also shown in Table 2. The principal differences from the baseline scenario include; a shift from local wheat cultivation to teff on land type A, the substitution of the new improved wheat variety for local wheat on land type B, and the substitution of eucalyptus for part of the maize crop on land types B, C and for wheat and other crops on land type D. Planting of eucalyptus for commercial purposes 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 substantial increases in yields; in some instances yields have doubled or even tripled. This is in line with projections by Wrigley et al., 1969, as quoted in Mpairwe, 1998.

Cultivation of the local wheat variety still persists on Land Type A even when farmers have the option of adopting the new high yielding variety (ET 13). This can be attributed in part to the high labour demands for planting the new variety, which are observed to be 24% higher than those of the local variety. More importantly, land type A is relatively flat and low lying so that cultivation of the new variety requires a thorough ploughing, making of furrows with the BBM plough, and construction of a communal drain with a complete system of feeder drains for improved drainage, as well as purchase and use of certified seeds and fertilizer. It is also likely that, though yields of ET 13 are higher than those of the local variety, the high labour requirements (especially for male labour) conflict with the high labour demand for teff cultivation, which is the preferred staple in the watershed. The relatively low labour demand during peak labour periods (i.e. land preparation, planting, and harvesting) in growing traditional wheat enables the farmer to have adequate time to cultivate and manage the highly labour intensive teff. These factors contribute to the relative attractiveness of continuing with the local wheat variety. However, the advantages of the local variety are likely to diminish over time as the cumulative effects of soil

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[10] This is the recommended level of consumption for adult males in Ethiopia.

erosion on yield leads to higher fertilizer applications, favouring a switch to more fertilizer-responsive varieties such as ET 13.

As illustrated in Figure 5, the introduction and uptake of these JVP technologies means that net nutrient balances are reduced to -72kg N, +4.5kg P and -59kg K. These values represent a reduction in aggregate nutrient loss of just over 26% compared with the baseline scenario[11]. The impact on potassium is least, and there is a substantial effect on nitrogen and phosphorous balances.

4.4 Robustness of the JVP Technologies Faced with Increased Nutritional Demands

As an additional test of the robustness of JVP technologies the implications of increasing nutritional requirements to 3000 calories per adult equivalent per day and greater than average annual population growth (3%) are illustrated by the results presented in Table 3. These results are compared with those in the baseline scenario to illustrate the performance of the adopted JVP technologies when nutritional demands within the watershed increase at a faster rate from a higher base (Figure 6).

These results show that increasing nutritional demands through improving nutritional standards and faster population growth has some impact on land use patterns and soil loss across the watershed. The area of teff is reduced slightly. At the same time, local wheat on Land type A is replaced by increased production of the improved wheat variety on land type B, while maize and other crops are substituted for eucalyptus on land type D. Increased grain consumption requirements are met mainly by reducing grain sales to less than 50% of baseline values (about 85% of those shown in Table 2), involving a reduction of approximately 58% in annual teff sales, though wheat sales actually increase by approximately 10% of those in Table 2. Accordingly, cash incomes are around 85% of those in Table 2, while soil erosion increases by around 5%.

Changes over the planning horizon in this scenario would suggest that as nutritional demands increase, and soil erosion generates pressure on yields of traditional crops, the new wheat variety continues to be substituted for pulses on land type B, reducing the scope for effective crop rotation on this land category. In addition there is a reduction in eucalyptus cover on land type D, replaced by increased production of maize and other crops. The result is a slight rise in erosion levels and an asymmetric impact on incomes. The increase in incomes (compared with Table 2) in the early years (probably reflecting the reduced commitment of land to eucalyptus planting) is followed by a significant reduction in later years as the impact of increased soil erosion on yields intensifies the impact of increased nutritional requirements on grain sales. Another interesting phenomenon is the appearance of fallow in the early years, as land previously reserved for eucalyptus is kept out of production, thereby gleaning the benefits of reduced soil erosion while at the same time ensuring that the land is available for cultivation in later years.

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[11] To assess the contribution of livestock to the reduction in nutrient loss we compare these losses with those that would arise if there is no application of dung manure on crops. This would sever the nutrient cycling process since failing to apply manure would mean that nutrient losses through livestock are not replenished and hence nutrient mining occurs at significantly higher rates. With no dung manure application, nutrient balances are calculated at -92kg N, -2.4kg P and –59kg K, approximately 10 per cent below baseline values. Thus the proper integration of livestock into the cropping system has the potential of more than doubling the reduction in nutrient losses, though this may vary depending on how animal waste is handled.

These results show that the adoption of the integrated intervention package can significantly reduce soil losses, even when higher consumption targets must be met. However, supporting significantly higher consumption levels at high rates of population growth introduced strains on the watershed system. In particular the model provides some evidence that the initial large reductions in soil loss may not be sustainable in the longer term as the system struggles to support higher production levels. One effect is a switch from eucalyptus planting to food crops in order to meet nutritional demands, even in the early years of the simulation period, that has implications for soil erosion and thus for yields in later years. We may speculate whether these impacts would have been identified if we had assumed a longer planning horizon (and the more established property rights that this would imply) that would have allowed the cumulative effects of soil loss on yields to become more substantial. It is also open to speculation whether the cost of installing a communal drain on land A might have been justified in such a longer horizon model.

5. CONCLUSIONS AND POLICY IMPLICATIONS

The bio-economic modeling approach used in this study 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 simultaneously assess socioeconomic and environmental impacts of technology interventions.

The model results indicate the potential for real income gains for watershed producers arising through rationalization of crop growing between the different land categories, adjusting animal numbers and establishing forestry enterprises on the upper slopes. Net cash incomes for the farmers in the watershed could rise by as much as a factor of around two-and-a-half over those prevailing before intervention and by just over a factor of two in the high nutrition scenario. However, these gains are eroded by the need to meet increased nutritional demands arising both from increasing consumption levels and population growth.

Rising nutrition demands are likely to reduce cash incomes, impact negatively on net nutrient balances by reducing the level of crop rotation among legumes and cereals, and increase soil erosion. One key impact here is that the relative viability of some of the JVP technologies changes. For example, the new wheat variety becomes increasingly important with higher population growth rate and higher calorie intake while at the same time there is a reduction in the area under eucalyptus, demonstrating the potential role of population growth in the development and adoption of innovations. This observation (that new wheat varieties become important at higher population densities) lends support to the population induced innovation argument. Similarly, the observation that these varieties are increasingly needed to arrest soil degradation as well, appear to support the conservation induced innovation argument.

The modeling undertaken in this study also reveals the potential benefits of adopting the integrated technology package. Livestock play a significant and potentially positive role here though mainly in conjunction with other elements of the technology package. Over the simulation period, soil losses are shown to continue at a high, although reduced rate, but relative nutrient losses are reduced and even reversed when the technology is adopted. However, this relative advantage may not be robust to increases in the required nutritional levels, especially in the presence of high rates of population growth.

Model estimates also show a high correlation between soil nutrient balances and soil erosion in the watershed, though this varies by nutrient. Nitrogen, for instance, shows less correlation with soil erosion especially in the last 5 years of the planning horizon, as a consequence of inflows of dung and chemical fertilizer to replace losses arising from soil erosion and crop harvests. Phosphorous losses are more closely related to erosion but losses are less significant due to the impacts of DAP fertilizer application used mainly to replenish nitrogen. Potassium balances exhibit a strong and direct positive relationship with erosion quantities reflecting that dung is the only source of potassium inflow.

In practice, however, there are significant barriers to accomplishing this major shift in farmer behaviour, including lack of capital, and insecurity of land tenure. These barriers will need to be overcome before the full benefits identified here can be realized. At the same time the possibility that these gains might be further eroded by increased nutritional demands must be carefully considered.

Thus, from a policy standpoint, it is clear that well targeted policies that provide incentives to use land according to suitability and comparative advantage can enhance overall social welfare by increasing income as well as by reducing degradation. The dichotomy between private and communal actions must be recognized and an appropriate policy environment created with a view to increasing their joint effectiveness. In particular, care should 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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Table 1 Agricultural Activity in the Ginchi Watershed: Actual 1995 levels and Results from the Baseline Scenario (without JVP technology, 1500 calories per adult equivalent per day, 2.3% annual population growth)

Activity by Land Type[1]	Actual 1995 Levels	Model Scenario 1 Results				
		Year I	Year II	Year IV	Year VII	Year XII
Land Type A						
Teff (ha)	27	20	35	20	20	20
Local Wheat variety (ha)	10	15	-	15	15	15
New Improved Wheat variety (ha)	-	-	-	-	-	-
Maize (ha)	-	-	-	-	-	-
Hay (ha)	-	13	13	13	13	13
Other Crops (ha)	13	5	5	5	5	5
Grazing / fallowing (ha)	3	-	-	-	-	-
Eucalyptus (ha)	-	-	-	-	-	-
Land Type B						
Teff (ha)	68	40	40	40	40	40
Local Wheat (ha)	10	-	33	18	18	18
New Improved Wheat Variety(ha)	-	-	-	-	-	-
Maize (ha)	1	-	5	20	20	20
Hay (ha)	7	15	15	15	15	15
Other Crops (ha)	21	60	22	22	22	22
Grazing/fallowing (ha)	9	1	1	1	1	1
Eucalyptus (ha)	-	-	-	-	-	-
Land Type C						
Teff (ha)	15	-	-	-	-	-
Wheat (ha)	8	-	-	-	-	-
Maize (ha)	1	20	28	20	20	20
Hay (ha)	3	7	7	7	7	7
Other Crops (ha)	6	2	2	10	10	10
Grazing/fallowing (ha)	8	12	4	4	4	4
Eucalyptus (ha)	-	-	-	-	-	-
Land Type D						
Teff (ha)	16	-	-	-	-	-
Wheat (ha)	2	-	38	40	-	-
Maize (ha)	6	-	2	-	-	-
Hay (ha)	7	13	13	13	13	13
Other Crops (ha)	16	40	-	-	40	40
Grazing / fallowing (ha)	6	-	-	-	-	-
Eucalyptus (ha)	-	-	-	-	-	-
Cows (No)	120	120	120	120	120	120
Oxen (No)	240	240	240	240	240	240
Teff Buying (kg)	12701	-13620	-107640	-76892	-60223	-38049
Wheat Buying (kg)	7106	5340	-136550	-118330	-48594	-38550
Cash Income (US$)	21342	19508	45143	30351	17729	13531
(average cash income(US$) per ha)	(72)	(65)	(151)	(102)	(59)	(27)
Erosion (tons per hectare per year)	31	18	22	22	20	20

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[1] Note that land use data refers to wet season uses only. In the dry season the land is predominantly used for grazing with the exception of crops sown late in the wet season, either to avoid water-logging in the early part of the season, or as a second crop to take advantage of residual moisture. These latter crops are mainly spices.

Table 2 Agricultural Activity in the Ginchi Watershed: Results from the 'JVP Adoption' Scenario (with JVP technology, 2000 calories per adult equivalent per day, 2.3% annual population growth)

Activity by Land Type[1]	Model Results				
	Year I	Year II	Year IV	Year VII	Year XII
Land Type A					
Teff (ha)	20	35	35	20	21
Local Wheat variety (ha)	15	-	-	15	14
New Improved Wheat variety (ha)	-	-	-	-	-
Maize (ha)	-	-	-	-	-
Hay (ha)	13	13	13	13	13
Other Crops (ha)	5	5	5	5	5
Grazing / fallowing (ha)	-	-	-	-	-
Eucalyptus (ha)	-	-	-	-	-
Land Type B					
Teff (ha)	40	40	40	40	40
Local Wheat (ha)	-	-	-	-	-
New Improved Wheat Variety(ha)	-	13	52	40	40
Maize (ha)	-	-	-	-	-
Hay (ha)	15	15	15	15	15
Other Crops (ha)	52	39	-	12	-
Grazing/fallowing (ha)	1	1	1	1	1
Eucalyptus (ha)	8	8	8	8	8
Land Type C					
Teff (ha)	-	-	-	-	-
Wheat (ha)	-	-	-	-	-
Maize (ha)	20	20	20	20	20
Hay (ha)	7	7	7	7	7
Other Crops (ha)	2	2	2	2	2
Grazing/fallowing (ha)	4	4	4	4	4
Eucalyptus (ha)	8	8	8	8	8
Land Type D					
Teff (ha)	-	-	-	-	-
Wheat (ha)	-	10	-	-	-
Maize (ha)	-	-	10	10	10
Hay (ha)	13	13	13	13	13
Other Crops (ha)	10	-	-	-	-
Grazing / fallowing (ha)	-	-	-	-	-
Eucalyptus (ha)	30	30	30	30	30
Cows (No)	120	800	796	796	796
Oxen (No)	240	75	77	77	77
Teff Buying (kg)	18380	-73912	-51020	-30175	-3165
Wheat Buying (kg)	37340	-843	-84467	-67878	-39894
Cash Income (US$)	4042	36586	150150	20040	46893
(average cash income(US$) per ha)	(14)	(123)	(504)	(67)	(157)
Erosion (tons per hectare per year)	13.69	15	14	14	14

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[1] Note that land use data refers to wet season uses only. In the dry season the land is predominantly used for grazing with the exception of crops sown late in the wet season, either to avoid water-logging in the early part of the season, or as a second crop to take advantage of residual moisture. These latter crops are mainly spices.

Table 3 Agricultural Activity in the Ginchi Watershed: Results from the 'High Nutrition' Scenario (with JVP technology, 3000 calories per adult equivalent per day, 3% annual population growth)

Activity by Land Type[1]	Model Results				
	Year I	Year II	Year IV	Year VII	Year XII
Land Type A					
Teff (ha)	20	20	20	20	35
Local Wheat variety (ha)	6	7	-	-	-
New Improved Wheat variety (ha)	-	-	-	-	-
Maize (ha)	-	-	-	-	-
Hay (ha)	13	13	13	13	13
Other Crops (ha)	14	5	5	5	5
Grazing / fallowing (ha)	-	8	15	15	-
Eucalyptus (ha)	-	-	-	-	-
Land Type B					
Teff (ha)	40	40	40	40	49
Local Wheat (ha)	-	-	-	-	-
New Improved Wheat Variety(ha)	-	52	52	47	43
Maize (ha)	32	-	-	5	-
Hay (ha)	15	15	15	15	15
Other Crops (ha)	12	-	-	-	-
Grazing/fallowing (ha)	9	1	1	1	1
Eucalyptus (ha)	8	8	8	8	8
Land Type C					
Teff (ha)	-	-	-	-	-
Wheat (ha)	-	-	-	-	18
Maize (ha)	20	20	20	20	-
Hay (ha)	8	8	8	8	8
Other Crops (ha)	2	2	2	2	2
Grazing/fallowing (ha)	3	3	3	3	5
Eucalyptus (ha)	8	8	8	8	8
Land Type D					
Teff (ha)	-	-	-	-	-
Wheat (ha)	-	-	-	-	18
Maize (ha)	-	12	15	18	-
Hay (ha)	13	13	13	13	13
Other Crops (ha)	23	-	-	-	-
Grazing / fallowing (ha)	-	6	3	-	-
Eucalyptus (ha)	17	22	22	22	22
Cows (No)	120	783	794	792	781
Oxen (No)	240	83	78	79	78
Teff Buying (kg)	18380	-53511	-33933	-8129	-4308
Wheat Buying (kg)	0	-91549	-56625	-20277	-3905
Cash Income (US$)	8569	45041	114410	17218	33765
(average cash income(US$) per ha)	(29)	(151)	(384)	(58)	(112)
Erosion (tons per hectare per year)	14	14	14	14	17

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[1] Note that land use data refers to wet season uses only. In the dry season the land is predominantly used for grazing with the exception of crops sown late in the wet season, either to avoid water-logging in the early part of the season, or as a second crop to take advantage of residual moisture. These latter crops are mainly spices.

Figure 1: Estimated Nutrient outflows in Ginchi Watershed based on 1995 Land Use Patterns

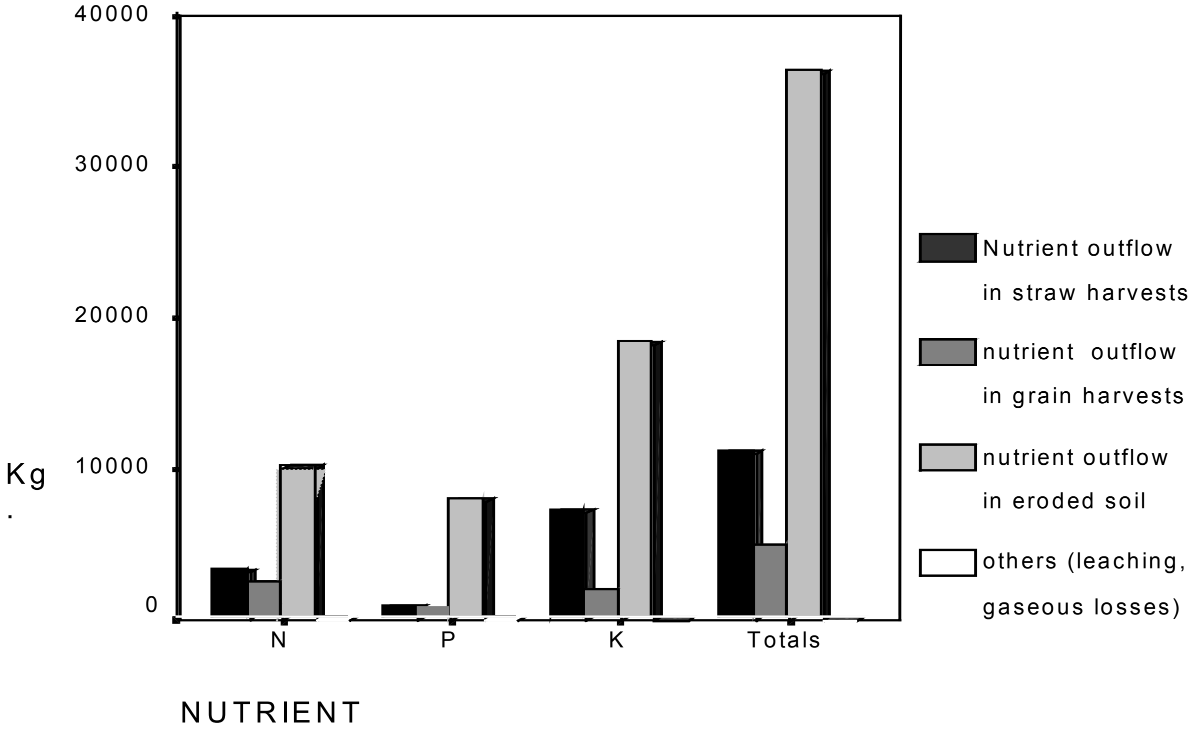

Figure 2. Livestock Numbers, Cash Income and Soil Erosion for Selected periods in the simulated Baseline Scenario assuming fertilizer use as the only major intervention compared with observed 1995 levels

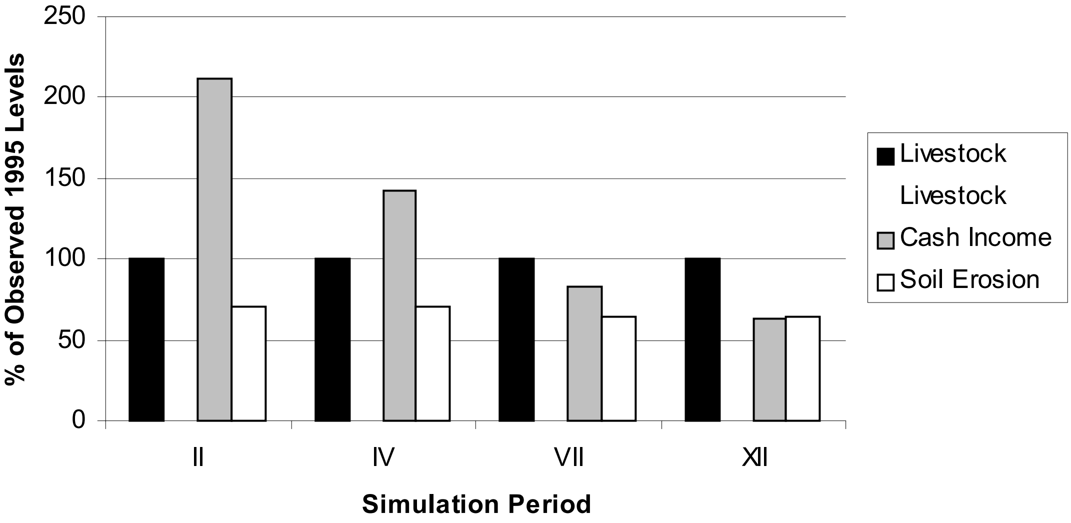

Figure 3: Annual nutrient balances with limited intervention and below average calorie consumption

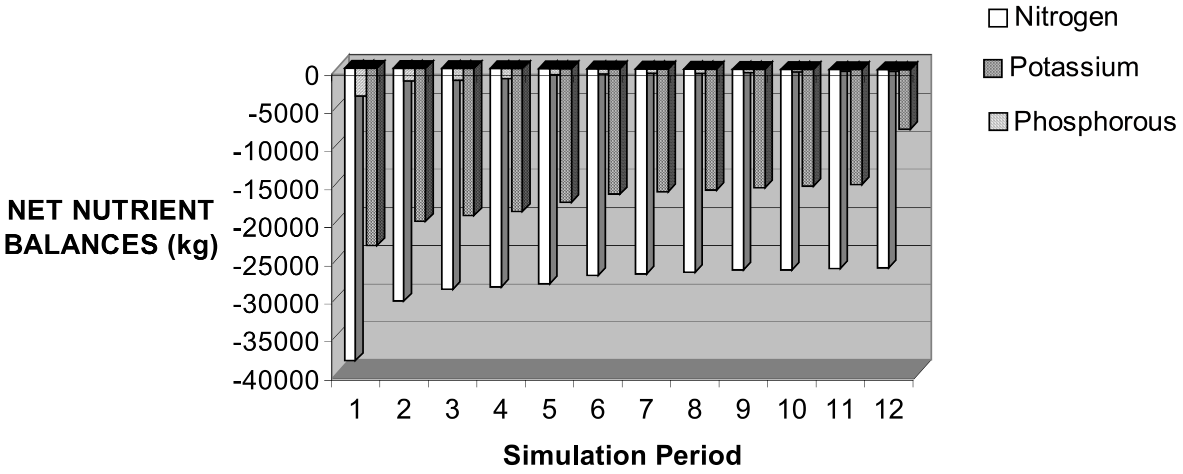

Figure 4. Impact of Adopting JVP Technology on livestock Numbers Grain Sales, Cash Income and Soil Erosion: Comparisons with the Baseline Scenario

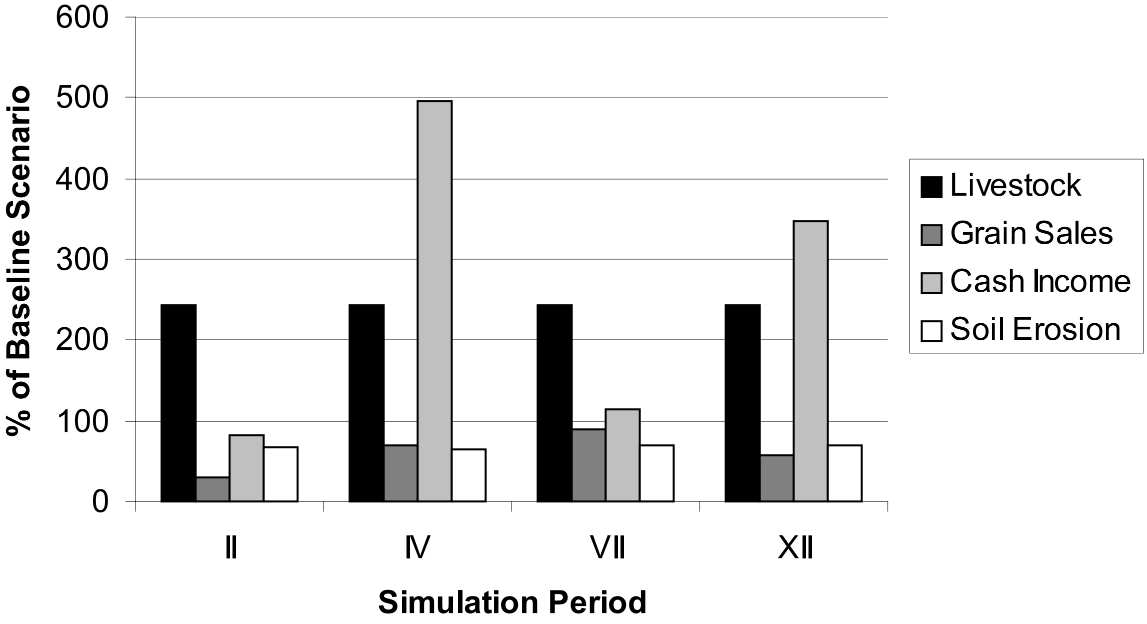

Figure 5: Nutrient balances under intervention, with dung manure application and consumption at recommended levels

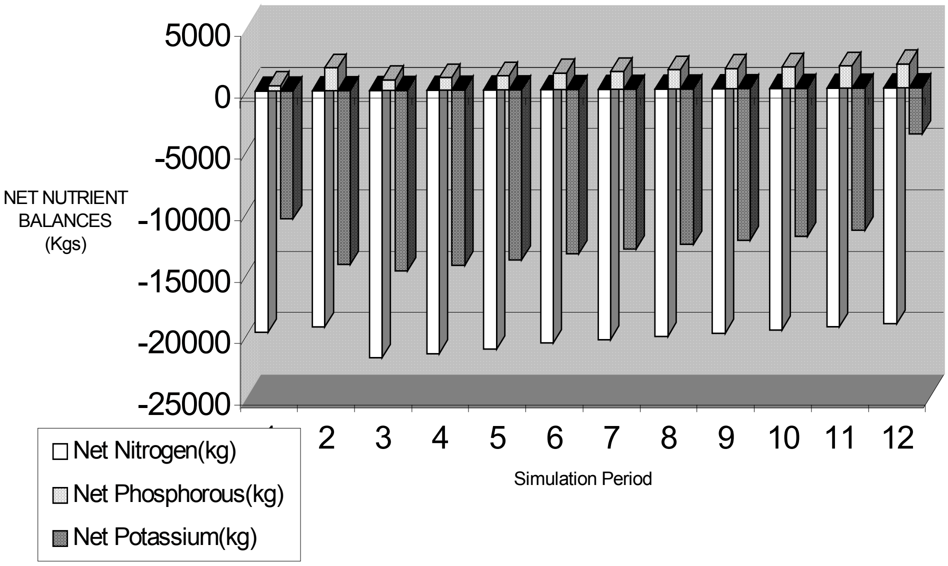

Figure 6. Effect of Higher Nutritional Demands on Livestock Numbers, Grain Sales, Cash Income and Soil Erosion: Comparisons with the Baseline Scenario