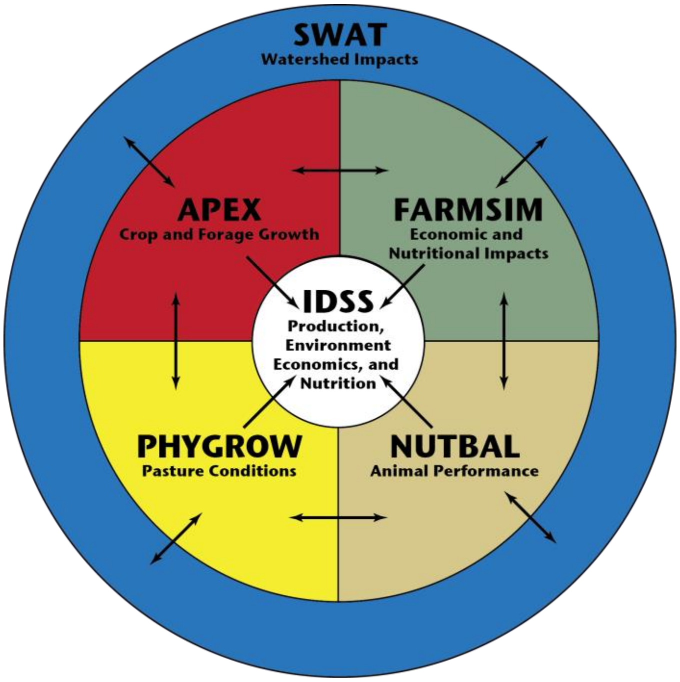

Demonstration of the Integrated Decision Support System (IDSS)[1] for Evaluation of New Farming Technologies at Village and Watershed Levels In Ethiopia

Texas A&M AgriLife Research

May 2013

Foreword

This report covers the work done under Work Order #1of the BMGF contract with Texas A&M AgriLife Research to evaluate the utility of the Integrated Decision Support System (IDSS) for use by the Bill and Melinda Gates Foundation. Plans for this study evolved from a series of interactions between senior staff of the Foundation and representatives of the team of scientists that developed and are using the major components of the IDSS. This document is proposed as the final report under Work Order #1. Modifications and additions were made to the first draft of the pilot study report, submitted in January 2013, in accordance with discussion and guidance from Foundation administrators. An addition to the first draft was made covering the mission to

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[1] The first draft of the Pilot Study Report used the term "Global Decision Support System" to describe this suite of models. Based on further discussions, this new descriptor was adopted as being more descriptive of the intent and function of the methodology.

Ethiopia in April, 2013 to present the pilot study for evaluation and follow on planning. Following presentation and discussion of the first draft of this report, the Foundation funded a second work order to continue and expand the evaluation and planning for possible application of the IDSS in Ethiopia and beyond.

The focus of the pilot study was on demonstrating the IDSS methodology to assess the integrated consequences of the introduction of new technology or management to sustainably improve the lives of smallholder subsistence farmers. The approach was to select a developing country site where most of the data needed to exercise this suite of models was in hand or available from existing sources. Because of our previous experience in the area and its immediate interest to national and international efforts to introduce improved farming system practices, the Lake Tana basin in Ethiopia was chosen as the area for the demonstration study.

This demonstration study was done to inform decisions by the Foundation on the selection and application of the IDSS for additional studies involving broader geographic dimensions and evaluation of more comprehensive approaches to enhancing the livelihood and wellbeing of smallholder families in the developing world. The initial pilot study leaves for future analysis the more detailed evaluation of several areas of infrastructure and policy development that will be needed to enable the adoption of the new technology and management proposed in the examples used in these studies.

Because of the obvious mutual interest in these demonstration studies, Texas A&M AgriLife Research has co-shared the cost of these studies in at least an amount equal to the Gates Foundation investment. As shown in the appendices of this report, we bring to the study a very large set of existing databases and methodologies and have made a substantial matching investment by providing time and energy of our senior faculty.

Substantial inputs in the form of shared databases, results from previous studies, and detailed knowledge and expert opinions were provided through consultations with national and international players such as the International Water Management Institute, The International Livestock Research Institute, and The International Center for Agricultural Research in Dry Areas and leadership of the Ethiopian Agricultural Transformation Agency.

The report consists of a narrative organized under the following sections, followed by a series of more comprehensive appendices that show the detail of background, methodologies, and results.

1. Introduction and Summary

2. Framing the study
    - Geographic description of the two site locations and the rationale for their selection and reference to detailed information in the appendices

- Description of the aggregation of household/subsistence farms into their related kebele and associations for the analysis
- Description of the sources and acquisition of data from our recent and ongoing studies and from colleagues and government officials in the Government of Ethiopia

3. Biophysical analyses using SWAT and APEX models and related databases
   - Brief description of models and data with reference to appendices
   - SWAT analysis of hydrology and soil erosion for the Gumera and Rib watersheds which contain the two more intensively studied kebele
   - Results from modeling several farming system scenarios in the Shena and Weg- Arba Amba kebele
   - Linkages between SWAT, APEX, and FARMSIM inputs and outputs

4. Economic and Nutrition analyses
   - Brief description of models and data with reference to appendices
   - Linkages of FARMSIM to APEX and SWAT (farm and watershed)
   - Summary of economic and nutrition results
   - Scale up of economic and nutrition results to the river basin scale

5. Conclusions
   - Demonstration of the utility of the IDSS
   - Enabling technology, policy, infrastructure – a next step
   - Further engagement with BMGF staff for planning phase 2

Introduction, Objectives and Summary of Results

The IDSS is comprised of a suite of previously validated spatially explicit models (SWAT, APEX, and FARMSIM) and databases that have been extensively applied in both U.S. and international settings. It provides an integrated approach linking production, economic, and environmental consequences of the introduction of new technology, policy, and training for decision makers in agriculture at multiple temporal and spatial scales.

SWAT (Soil and Water Assessment Tool) is a biophysical simulation model that operates on a daily time step and is widely used in the US and internationally to quantify the impacts of land management practices on stream flows and water quality in large complex watersheds or river basins. It uses geographic information systems to manage input and output data, can be run on personal computer systems, and is sensitive to weather, topography, soils, land use/land cover, and agricultural management practices.

APEX. (Agricultural Policy Environmental Extender**)** is a biophysical simulation model that shares many of the attributes of SWAT. It is used to evaluate detailed crop management technologies and decisions that can affect agricultural production and environmental sustainability (soil, water, greenhouse gases, etc.) at the scales of individual fields, whole farms, or small watersheds. APEX receives inputs on forage availability from the Phytomass Growth Model (PHYGROW). Appendix 1 provides a historical summary of the development of SWAT, APEX, and several predecessor models.

FARMSIM is farm level Monte Carlo simulation model used to perform economic and nutrition analysis. The FARMSIM model simulates a representative farm for five years using stochastic market prices, crop yields, and livestock production values. The model is recursive in that the financial values at the end of year are the beginning financial values for the start of next year. Livestock numbers are simulated over time based on parameters for fractions for animals consumed, die, culled, and stochastic birthrates. (A detailed description of FARMSIM is provided in Appendix 10.). In future iterations of the IDSS, we plan to use the Nutritional Balance Analyzer (NUTBAL) for enriching the modeling the livestock component of mixed farming systems. This model includes a description of the animals, their body condition and other factors that relate to the amount of meat and milk produced. This will serve as a refined input to FARMSIM.

For the IDSS, SWAT, and FARMSIM are designed to allow the outputs and inputs from each model to be used by the others. In addition, each model draws on inputs from external sources, such as FAO, NOAA, and USGS natural resources databases, IPMS Baseline surveys, key informants, and others.

We propose that BMGF use the IDSS as a planning, evaluative and teaching methodology to compare the relative merits of future research and development investment options and the impacts, both intended and unintended, of these investments as they emerge and are applied.

The Pilot Study

To evaluate and demonstrate the utility of these methods for the Gates Foundation and its developing country partners, a pilot study was conducted for Ethiopia, in which the multiple impacts of several levels of faming system intensification were evaluated at the peasant association (kebele) and river basin scales. The studies were done for the Weg-Arba Amba and Shena kebele and the Gumera and Rib River basins near the eastern shore of Lake Tana. Input data for the models were obtained from international data bases, previous IDSS studies and from recent studies sponsored by the BMGF and other donors. The results clearly suggest the utility of the IDSS in quantitatively forecasting the differences in yields, economic and nutritional impacts, and environmental consequences of the new farming technologies. The ability to use input and management trade-offs to optimize these outcomes was also evident. The importance of variables such as policy, availability of capital, access to markets, and changes in social mores was clearly revealed and forms the basis for future studies building on this demonstration. The broader application of the IDSS in other countries is evident.

Framing the Study

IDSS Demonstration Sites

We selected the Fogera Woreda, located within the Gumera and Rib river basins on the eastern side of Lake Tana in the South Gondar, Amara region of Ethiopia (Fig. 1) to demonstrate the capabilities of the IDSS. Selection of this woreda was based on availability of data from:

previous hydrologic studies with the SWAT model of the Blue Nile and Lake Tana watersheds, the ongoing IPMS study (IPMS Atlas 2007, Fogera Woreda, Amhara), and the Fogera Woreda Pilot Learning Site Diagnosis and Program Design document (2005).

The IPMS Atlas provides the following information about the Fogera woreda. The total land area of the Woreda is 117,405 ha, with flat lands accounting for 76%, mountain and hills 11%, and valley bottoms 13%. The total population of the Woreda is 233,529, with a rural population of 206,717. The male and female populations are similar in both rural and urban areas. The number of agricultural households is 42,746. The average land holding is about 1.4 hectares, with minimum and maximum holdings of 0.5 and 3.0 hectares respectively. Appendix 2 of this report includes maps of the kebele, topography, soils and land uses of Fogera woreda.

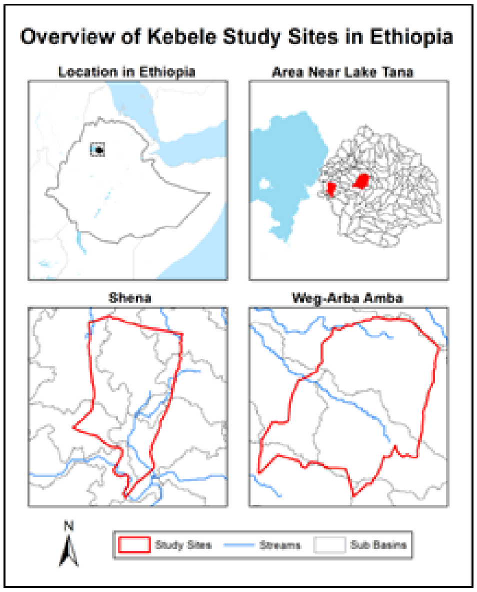

Figure 1. Location of study site on the eastern shore of Lake Tana in Ethiopia.

Within the Fogera woreda, we used spatial analysis to select two major river watersheds and two kebele, often referred to as peasant associations (PAs). In selecting specific areas for analysis, we used metrics that a public or private organization might employ to identify an area for possible agricultural development investment. Based on these criteria, we selected the Shena and Weg-Arba Amba kebele, which are located within the Rib and Gumera river basins, respectively, both of which drain into Lake Tana.

The Shena kebele is located on nearly level land within the Rib river basin near Lake Tana at elevations of 1774 m to 1850 m. Land uses include cultivated cropland, dense shrub land, open forest, grassland, exposed sand/soil, and seasonal swamp. Cropping systems are dominated by rice, finger millet, horticultural crops, and noug; however, in recent years noug and finger millet are being replaced by maize and rice. Livestock include cattle, sheep and chickens.

Weg-Arba Amba kebele is located in the Gumera river basin on rolling land with elevations ranging from 1774 m to 2153 m. The kebele is predominantly grassland with significant amounts of cropland, dense shrub land, and open forest. Cropping and livestock systems below 2000 m are dominated by maize, teff, finger millet, noug, vegetables, cattle and goats. Above 2000 m barley, horse beans, potatoes, sheep and cattle are produced. Most of the crop land is at the higher elevations.

Biophysical Modeling

A main objective in simulating crop - livestock systems in the highlands of Ethiopia was to demonstrate that the IDSS can efficiently produce *ex ante* analyses of complex agricultural technologies designed to increase food production, improve nutrition, enhance economic well-being, and minimize negative environmental consequences. An additional objective was to demonstrate that the IDSS can effectively be used to evaluate agricultural systems at different spatial (river basin, subbasin, farm, or field) and temporal scales (monthly, annual, or long-term).

We used the SWAT and APEX cropping systems models of the IDSS to simulate current low-input and possible future higher input cropping systems. SWAT was used to simulate the river basin and subbasin scales. APEX was used to simulate cropping systems operating at the village (or, in Ethiopia, kebele) scale.

For both APEX and SWAT, outputs included crop yields, crop yield responses to irrigation and fertilizer inputs, the amounts of irrigation and fertilizer needed to maximize yields, the biophysical stresses (temperature, water, nitrogen) that limited crop growth and yields, and the effects of the selected cropping systems on environmental indicators (such as runoff, shallow aquifer recharge, stream flows, soil erosion/sedimentation on uplands and in streams, nutrient losses from fields, and sediment, nutrient, pesticide, and microbial concentrations in streams). Only a few of these possible outputs are described in this report.

Crop Production Systems and Their Environmental Consequences.

Our first objective was to demonstrate that the IDSS can be effectively used at very different spatial scales. Past work has used SWAT to simulate the hydrology of the entire continent of Africa, for the Nile Basin, and for the Lake Tana Basin. Summaries of past SWAT studies for Africa and the distinctive capabilities of the two models are given in Appendices 3 and 4, respectively. For the current exercise, SWAT was used to simulate hydrology, soil erosion, and Baseline crop yields for the Rib and Gumera river basins. APEX was used to simulate several current and potential cropping systems for the Shena and Weg-Arba Amba kebele. For both sets of simulations crop yields, necessary irrigation and fertilizer inputs, and the environmental consequences of both current and high-input systems were simulated.

Input data. The APEX and SWAT models require identical inputs for daily weather, topography, soils, and land use/land cover. The topography and land use/land cover data were derived from USGS sources. Daily weather data were obtained from the NOAA-USGS Climate Forecast System Reanalysis (CFSR) global daily weather database. This 32-year (1979-2010) daily weather data base, which we provide to SWAT and APEX users worldwide, contains data for precipitation, minimum and maximum temperatures, solar radiation, wind speed, and humidity. APEX and SWAT simulations of all cropping systems were for the entire 32-year record available from the CFSR weather database.

Soils data were obtained from the FAO 1:1 million world soils map and associated soil pedon data base. For APEX simulations a deep alluvial soil was used for the Shena kebele site, and a shallow rocky soil was used for the Weg-Arba Amba site.

River Basin and Subbasin Scale Simulations with SWAT

Initial basin-scale analysis

For the Gumera and Rib river basins, mean stream flows totaled almost 60% of mean total precipitation, the result of large amounts of runoff and subsurface flow during the wet season. These results are consistent with past studies in the Blue Nile basin (see Appendix 3) and suggest that, depending on location within the watersheds, ample water may be available, either for capture in small reservoirs or in shallow aquifers, for use as supplemental irrigation during the dry season.

Time series analyses. In most SWAT watershed simulations we evaluate the accuracy of multi-year estimation of monthly stream flows by comparing SWAT outputs with measured data at the same location in the watershed. In many cases systematic errors are identified that can be eliminated with the SWAT-CUP calibration tool provided on the SWAT website.

Figure 2 shows measured and simulated monthly flows in the Gumera River near its outlet to Lake Tana. The results (R^2=0.75 and NCSE=0.75) indicate that using internationally available weather and landscape data, SWAT accurately simulated monthly stream flows in this region of Ethiopia. These results are consistent with other SWAT-based studies for the entire continent of Africa and a number of African river basins (Appendix 3).

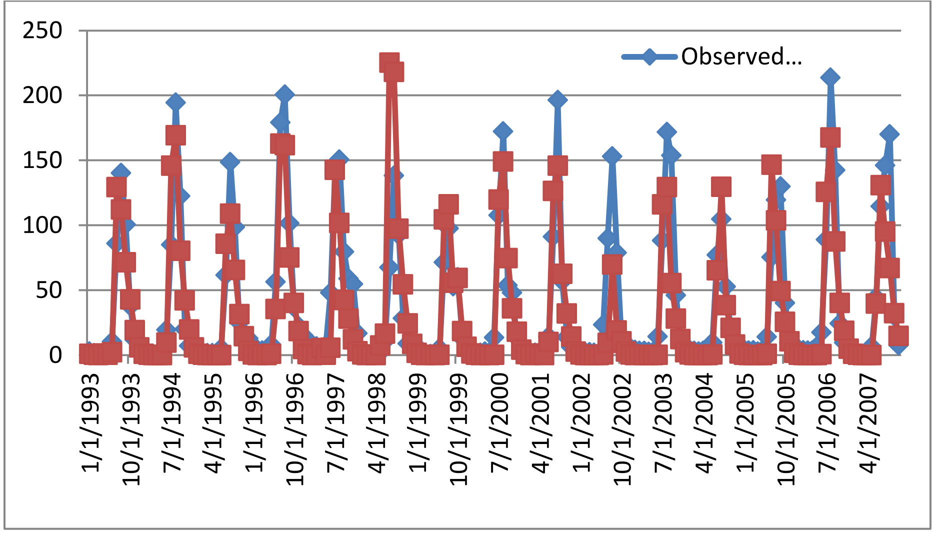

Figure 2. Monthly measured and simulated stream flows in the Gumera River measured near its outlet to Lake Tana.

Table 1 breaks down mean SWAT hydrology outputs by land use and cropping system for the combined Gumera and Rib watersheds. In this study, maize, teff, and grazing lands made up the great majority of land uses and crops in these simulations. Continuous maize, continuous teff, and maize-teff rotations simulated for a variety of mostly sloping soils. For the more level landscape near Lake Tana, a maize-rice-onion crop rotation was simulated.

Table 1. Simulated cropping systems, vegetation types, and mean annual hydrologic and soil erosion components for the combined Gumera and Rib watersheds. Continuous maize and teff crops are grown in the main wet season without irrigation.

Land Use	Area	Precipitation	Irrigation	Runoff	Subsurf.	ET	Erosion
	(km^2)	(mm)	(mm)	(mm)	(mm)	(mm)	(t/ha)
Cropland							
Maize	1,382	1,303	0	402	351	525	85
Teff	944	1,294	0	372	409	483	114
Maize-Rice-Onion	8	1,313	639	386	237	1,139	8
Grazing land	1,049	1,301	0	356	399	517	15
Forest land	5	1,345	0	269	488	557	<1
Village	3	1,278	0	472	279	503	<1

For the more sloping lands with maize and teff cropping systems, we simulated shallow clean tillage, no structural conservation practices, and complete residue removal (for animal feed). As reported by Ethiopian agricultural experts and other hydrologic studies of the region (Appendix 3), large erosion rates were estimated (Table 1). Rock barriers at the edges of many of the region's small fields undoubtedly produce field-edge sedimentation and reduce sediment delivery to streams in the region. SWAT and APEX are capable of simulating such effects, as well as soil and water conservation practices such as terraces, grassed waterways, riparian vegetation, "gully plugs," conservation tillage, no-tillage, ponds to collect runoff and detain sediment, and others. Future studies could evaluate the costs and benefits of such practices.

Subbasin scale analysis. Table 1 represents results averaged over the entire Rib and Gumera river basins. However, many types of spatial analysis are possible at the subbasin scale, including crop yields, hydrologic data, sediment and nutrient losses, and other model outputs. In addition, differences in scenarios can be visualized spatially. To illustrate how IDSS models can be used to analyze the impacts of crop management on soil erosion in different landscapes, we simulated the effects of two levels of crop management on soil erosion for all the subbasins of the Rib and Gumera basins. The two input levels were: (1) the Baseline (low-input) maize, teff, and maize-rice-onion cropping system in use in the region, and (2) the same cropping systems with additional nitrogen fertilizer and irrigation in the dry season (with rates determined by the automatic fertilizer and irrigation routines in SWAT). The results of this analysis are shown in Figure 3; green indicates large reductions in sediment yield; red indicates small or no reductions in sediment yield.

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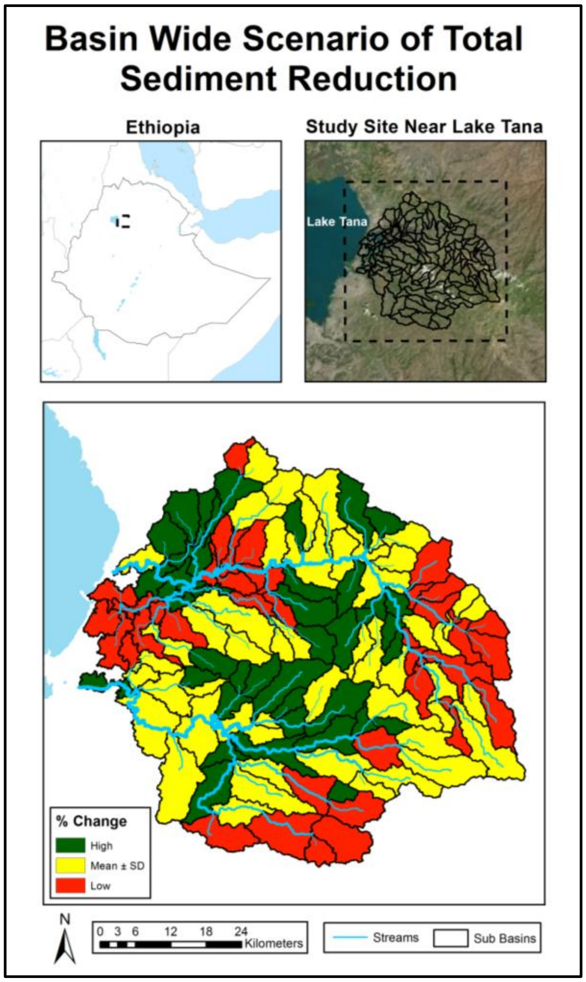

Figure 3. Spatial distribution of the impacts of changing from low nitrogen fertilizer rates for crop rotations including maize, teff, rice, and onion to high nitrogen fertilizer rates for the same crop rotations.

Figure 3 shows how the simulated increases in nitrogen fertilizer and irrigation reduced sediment delivery to streams in the subbasins of the Rib and Gumera watersheds. As expected, increasing fertilizer nitrogen rates and applying irrigation in the dry season stimulated crop growth, increased leaf area (which protected the soil during the rainy season), and reduced soil erosion. These reductions would likely be greater on the sloping croplands between the Gumera and Rib watersheds (the green areas in the middle of the figure) than on the more level lands near the outlets of the watersheds and in areas with lesser amounts of cropland in the eastern and southern parts of watershed. Maps of the topography, land use, and soils in the Fogera Woreda are given in Appendix 2. Similar analyses could estimate the impacts of widespread application of soil and water conservation practices and implementation of more intensive cropping systems. Based on these preliminary simulations, it is probable that sediment delivery to Lake Tana would be substantially reduced by implementation of more intensive cropping systems with appropriate conservation practices.

In most cases, government crop yield data are collected and published for political subdivisions within a country. For example, we obtained estimates of mean maize, teff, and rice yields for the South Gondar region of Ethiopia. Data were not available for smaller areas within South Gondar.

Therefore, we used SWAT to estimate crop production for Baseline and more intensive cropping systems for subbasins within the Rib and Gumera river basins. After calibration of SWAT for mean crop yields in the South Gondar region, we used the model to estimate the combined impacts variation in soils, topography, and management practices on maize, rice, and teff grain yields within this region. Sample results are given in Figure 4. The three maps on the left side of Figure 4 represent the current low-input Baseline cropping system used in the region. The three figures on the right side represent yields of crops receiving additional fertilizer and dry season irrigation. Subbasins highlighted in yellow had mean simulated grain yields within +/- 0.5 standard deviations of the basin mean for the low-input or the high-input treatment. Subbasins colored green had greater mean yields, and those colored red had lesser mean yields than the yellow subbasins. Note that for all three crops additional fertilizer and dry season irrigation substantially increased crop yields. For example, for maize grown with low fertilizer and no dry season irrigation, subbasins with near-mean yields (colored yellow) yielded between 2,163 and 2,545 kg/ha. In contrast, when additional fertilizer and dry season irrigation were simulated, subbasins with near-mean yields produced much more, between 3,596 and 4,395 kg/ha. As we would expect, some subbasins responded more strongly than others to increased inputs. For example, yields for subbasins with shallow and infertile soils might respond more strongly to increased fertilizer and irrigation than those with deep, fertile soils. More detailed analysis of these results could provide valuable information for extension personnel advising farmers or policy makers attempting to decide where to target government programs aimed at increasing yields.

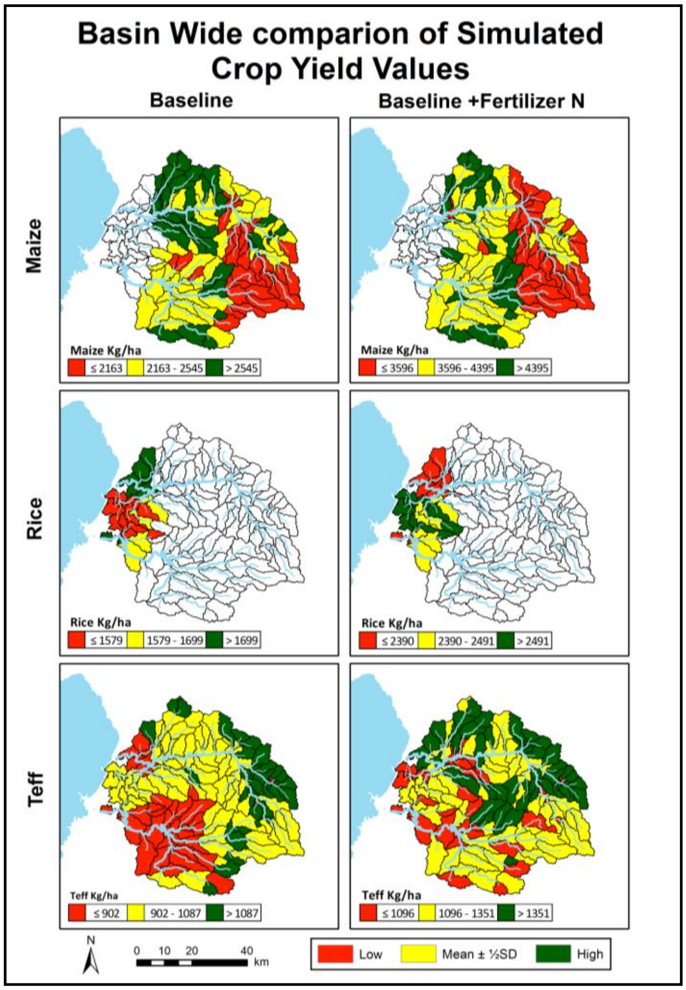

Figure 4. Comparison of simulated maize, rice, and teff grain yields in the Rib and Gumera river basins. Figures on the left are for Baseline farm management. Figures on the right are for crops receiving near-optimum fertilizer nitrogen and irrigation. Note that the yields of the figures on the right are greater than those on the left for low, near-mean, and high yielding subbasins.

More detailed information about the SWAT simulations, including time series of reported and simulated crop yields in South Gondar, can be found in Appendix 5.

Kebele Scale Simulations with APEX

Weg-Arba Amba Kebele

This kebele occupies an upland site with slopes ranging from 6 to 23 %. We chose a 7% slope for the cropland soils. According to Ethiopian agricultural experts, the two dominant crops in the area are corn and teff. Most of the farmers currently grow only one crop per year during the rainy season.

To demonstrate APEX's ability to assess fertilizer and irrigation requirements and effects in traditional grain cropping systems, we simulated continuous maize and continuous teff production under:

(1) current low-input, rainfed cropping system and management practices (Baseline), and

(2) a more intensive cropping system in which APEX was allowed to estimate and apply fertilizer and irrigation necessary to reduce nitrogen and water stress to near-zero (Baseline+N+I).

To demonstrate APEX's ability to simulate the impacts of improved crop genetics, we simulated:

(3) the use of genetically improved maize and teff varieties (represented by crops with a 15% increase in harvest index) in the Baseline+N+I cropping system (Baseline+N+I+V).

In addition to these scenarios, we simulated intensification of the current low-input system by adding grain legume or vegetable crops to the traditional grain crops in order to increase the protein or vitamin A yields of the existing system. The systems simulated were:

(4) a maize-chickpea relay cropping systems with current fertilizer inputs but supplemental irrigation of the chickpea during the dry season, and

(5) a maize-squash relay cropping systems with current fertilizer inputs but supplemental irrigation of the squash during the dry season.

For all cropping systems, immediately after grain harvest all crop residues were removed for animal feed, reflecting current and anticipated future needs for animal fodder. The results of these APEX simulations are summarized in Figure 5 and Table 2. Figure 5 graphically illustrates the effects of additional irrigation, nitrogen fertilizer, and improved crop germplasm on grain yields of maize and teff, as well as the potential to intensify the cropping system by adding relay crops near the end of the wet season. In addition to its simulation of crop growth and yields, APEX provides users with much more detailed information concerning weather, hydrology, soil erosion, water and nutrient stresses that limit growth, biomass production, and many other factors. This more detailed model output is summarized in Table 2.

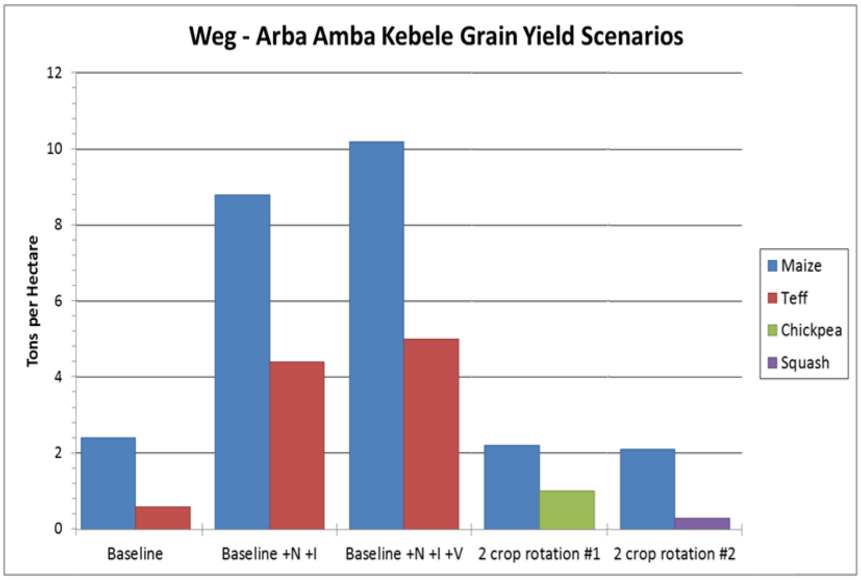

Figure 5. Simulated crop yields for continuous low-input maize and teff (Baseline) cropping systems; cropping systems with adequate irrigation and nitrogen fertilizer (Baseline +N +I); cropping systems with adequate irrigation, nitrogen fertilizer, and improved varieties; a low-input maize-chickpea relay cropping system; and a low-input maize-squash relay cropping system.

As might be expected, the low-input farming system represented by the Baseline scenario produced low grain yields due to nitrogen and drought stresses. These stresses are reflected in the large values of metrics for simulated nitrogen stress (NS) and water stress (WS) in Table 2.

Table 2. Weg-Arba Amba kebele simulated cropping systems.

Treatment**	Yield	Residue	FN	FP	Q	WYld	ET	IRGA	Y	WS	NS
	(t/ha)	(t/ha)	(kg/ha)	(kg/ha)	(mm)	(mm)	(mm)	(mm)	(t/ha)	(d)	(d)
Continuous Maize											
Baseline	2.4	2.3	56	40	406	681	562	0	30	14	65
Baseline+N+I	8.8	8.0	202	40	389	647	702	110	28	6	2
Baseline+N+I+V	10.2	6.8	202	40	389	646	703	110	28	6	2
Continuous Teff											
Baseline	0.6	1.1	24	17	372	648	596	0	33	23	31
Baseline+N+I	4.4	7.3	152	17	376	656	726	150	28	7	0
Baseline+N+I+V	5.0	6.8	152	17	376	656	726	150	28	7	0
Maize-Chickpea Relay Crop											
Maize	2.2	2.0	56	40	334	659	635	0	23	16	66
Chickpea	1.0	1.1	0	0	-	-	-	66	-	14	2
Maize-Squash Relay Crop											
Maize	2.1	2.0	56	40	331	666	739	0	24	16	67
Squash	0.3	0.6	40	0	-	-	-	184	-	3	46

**Grain/fruit yields (Yield), residue yields (Residue), fertilizer nitrogen (FN), fertilizer phosphorus (FP), runoff (Q), runoff + return flow to stream (WYld), evapotranspiration (ET), irrigation (IRGA), soil erosion (Y), water stress (WS), and nitrogen stress (NS).

APEX is sensitive to the abiotic stresses that usually limit crop yields, and it is able to dynamically estimate these stresses and simulate application of fertilizers and irrigation to minimize them. For example, for the Baseline+N+I scenario, APEX applied a mean of 202 kg/ha of fertilizer nitrogen and 110 mm of supplemental irrigation (Table 2). This caused mean grain yields to increase from 2.4 to 8.8 tons/ha and greatly reduced the metrics for nitrogen (NS) and water stress (WS) (Table 2). The model produced similar results for teff.

For the N+I+V scenario, we adjusted the maize and teff crop parameters to increase the grain harvest index by 15 percent, representing likely crop genetic improvements over the next several decades. As expected, APEX simulated increases in crop yields with essentially no impact on stresses. If necessary, a number of other crop parameters could be adjusted to more accurately represent the physiological and growth characteristics of future varieties, including: photosynthetic efficiency, leaf area development, rooting depth, plant height, nutrient requirements of the crop, and tolerance to pests.

The Maize-Chickpea Relay Crop scenario caused a slight reduction in maize yield due to inter-crop competition. In addition, since all chickpea residue was removed after harvest for animal fodder, no effect of residual legume nitrogen was observed on maize yields. Despite the slight negative effect on maize yields, adding an irrigated, dry-season chickpea crop to the Baseline maize cropping system can increase protein production with no additional fertilizer inputs.

The Maize-Squash Relay Crop simulates adding squash to the Baseline unirrigated maize cropping system to increase fresh vegetable production. Because the maize crop had taken up virtually all the available soil nitrogen by the time the squash was planted, and the rainy season normally ended before the squash matured, additional fertilizer nitrogen and irrigation were needed to obtain adequate squash yields. The two relay cropping treatments illustrate that APEX simulates plant competition for light, water, and nutrients. It also allows the user to fine-tune management practices (adding fertilizer nitrogen and irrigation) to minimize stresses due to that competition.

Serious soil erosion is occurring in the steep lands of the Ethiopian highlands, and the shallow and rocky soils of the Weg-Arba Amba kebele suggest severe soil erosion. These APEX simulations assumed clean tillage, no structural erosion controls, and removal of all crop residues for animal feed estimated annual erosion rates of over 20 tons per hectare. However, rocks that are cleared from the fields are commonly piled along the field borders. These act as terraces, and in areas with these structures erosion losses from the edge of the fields should be reduced by approximately 80 percent (data not shown).

Even with adequate fertilizer, runoff (Q) plus subsurface return flow to streams (WYld) are large, approaching total crop evapotranspiration (ET). This demonstrates that plenty of water is available for capture in small reservoirs for irrigation during the dry season. Simple low-pressure drip irrigation systems may be a useful technology to move farm families toward small-scale but intensive production of additional vegetable and/or grain legume crops. We are currently working with Mr. Yihun Dile, an Ethiopian PhD student in Sweden, to use IDSS models to estimate optimum placement, size, and management of small irrigation reservoirs.

Shena Kebele

The Shena kebele site is located on the near-level floodplain near the shores of Lake Tana (Figure 1). Four cropping systems were selected to demonstrate that APEX can simulate more complex cropping systems than those in the Weg-Arba Amba kebele. In addition to simulating the low-input Baseline maize-rice-onion rotation, we evaluated the effects of increasing levels of nitrogen fertilizer and growing improved crop varieties. A fourth two-year cropping system, consisting of a two-year maize-rice-onion-soybean-rice-onion rotation, was simulated to demonstrate the effects of including a grain legume to increase protein production without increasing nitrogen fertilizer rates. Results of these simulations are given in Figure 6, Figure 7, and Table 3.

Figure 6 shows that APEX predicted that increasing nitrogen fertilizer and planting improved varieties can greatly increase yields of both maize and rice. In addition, substituting soybean for maize every other year has relatively little effect on grain yield because soybean yielded almost as much as the severely nitrogen-stressed maize. However, Figure 7 indicates that because soybean much greater protein concentration than maize, the more complex two-year rotation produces much more protein for human and, perhaps, animal consumption.

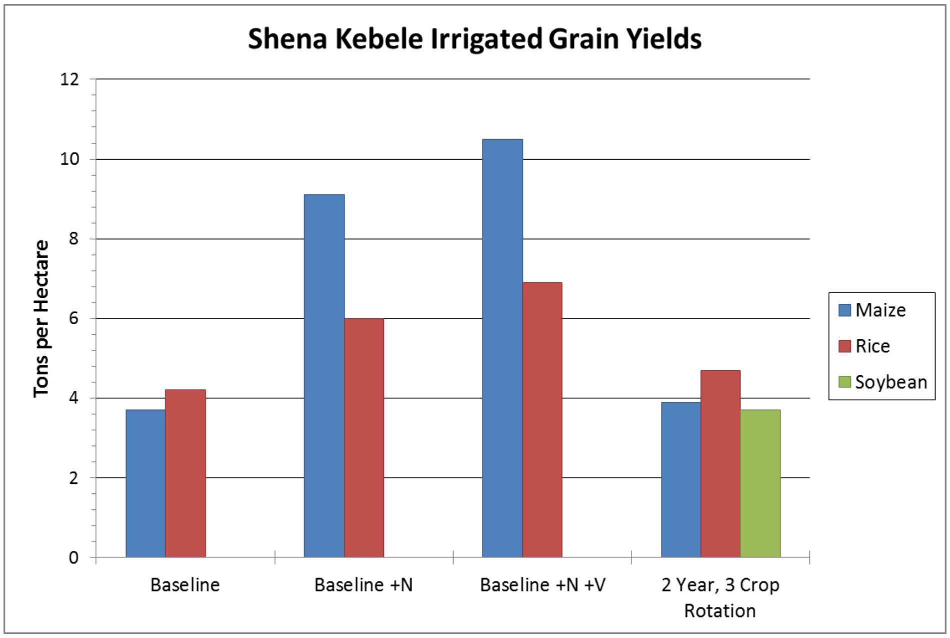

Figure 6. Simulated grain yields for irrigated maize, rice, onion rotation.

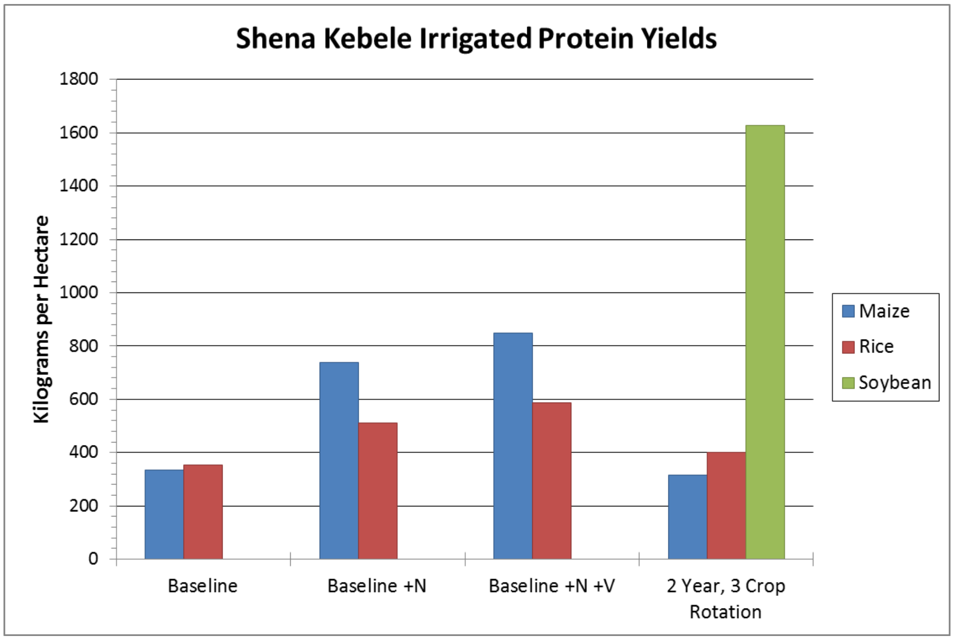

Figure 7. Simulated grain protein yields for irrigated maize, rice, onion rotation.

We have included Table 3 to illustrate that APEX provides a great deal more information about the performance of complex cropping systems than is included in Figures 6 and 7. The Maize-Rice-Onion Baseline scenario was a three-crop rotation of maize, rice, and onion. The rice was grown in paddies during the rainy season and received ample rainfall to maintain saturated or near-saturated soil conditions. Maize and onion were grown in the dry season and were irrigated at rates (IRGA) determined dynamically by APEX. Fertilizer rates for the Baseline cropping system were typical for the region, but APEX found that for this cropping system grain and onion yields are greatly limited by nitrogen stress (NS).

We simulated the Baseline+N scenario to demonstrate APEX's ability to estimate fertilizer N requirements and crop response. In response to crop N stress, APEX increased average annual fertilizer N application from the 101 kg/ha Baseline rate to 387 kg/ha. The additional fertilizer reduced N stress (NS) to near zero and increased average yields of maize, rice, and onion by 246%, 143% and 144%, respectively. It also almost doubled average annual protein production by the maize and rice crops. In addition, crop residue yields increased substantially, providing additional fodder for livestock (Table 3).

To demonstrate APEX's sensitivity to varietal improvement, we simulated the effects of growing crops with 15% greater harvest indexes with increased fertilizer N (Baseline+N+V scenario). As expected, APEX simulated greater yields, greater protein production, and slightly higher average nitrogen fertilizer requirements (402 kg N/ha) when varieties with increased yield potential were used (Table 3).

Table 3. Shena kebele simulated irrigated maize, rice, onion rotation.

Treatment**	Yield	Residue	FN	FP	Q	WYld	ET	IRGA	Y	WS	NS	Protein
	(t/ha)	(t/ha)	(kg/ha)	(kg/ha)	(mm)	(mm)	(mm)	(mm)	(t/ha)	(d)	(d)	(kg/ha)
Baseline												
Maize	3.7	3.4	23	0	266	363	1591	591	0.7	6	47	300
Rice	4.2	4.3	55	23	-	-	-	0	-	1	45	352
Onion	1.8	0.1	23	0	-	-	-	111	-	1	21	-
Baseline+N												
Maize	9.1	8.6	178	0	272	370	1597	605	0.7	7	1	737
Rice	6	6.2	138	23	-	-	-	0	-	1	1	510
Onion	2.6	0.2	71	0	-	-	-	108	-	1	0	-
Baseline+N+V												
Maize	10.5	7.3	179	0	272	370	1607	604	0.7	7	1	850
Rice	6.9	5.5	150	23	-	-	-	0	-	2	1	586
Onion	3.7	0.1	73	0	-	-	-	117	-	2	0	-
Irrigated Maize-Rice-Onion-Soybean-Rice-Onion Rotation (2 Years)												
Maize	3.9	3.6	23	0	266	363	1631	578	0.6	3	47	316
Soybean	3.7	8	0	0	-	-	-	684	-	5	0	1,628
Rice	4.7	4.9	55	23	-	-	-	0	-	3	34	400
Onion	1.9	0.1	23	0	-	-	-	111	-	1	19	-

**Simulated 2-year rotation of maize-rice-onion-soybean-rice-onion. Grain/bulb yields (Yield), residue yields (Residue), fertilizer nitrogen (FN), fertilizer phosphorus (FP), runoff (Q), runoff + return flow to stream (WYld), evapotranspiration (ET), irrigation (IRGA), soil erosion (Y), water stress (WS), nitrogen stress (NS), grain protein content (Protein).

To demonstrate the impact of grain legumes on protein production of complex cropping systems, we simulated replacing maize with soybean every other year in the Baseline cropping system (without additional fertilizer nitrogen). Introduction of soybean slightly increased maize and rice yields compared to the Baseline maize-rice-onion rotation, but average annual protein production of the entire cropping system increased substantially. This highlights the importance of including grain legumes in crop rotations to increase protein production of cropping systems where fertilizer nitrogen is limited (Table 3).

Appendix 6 contains more information about our APEX simulations for the Weg-Arba Amba and Shena kebele.

Field Scale Spatial Analysis

In addition to analyses at the basin, subbasin, and kebele scales, SWAT and APEX can be used to evaluate hydrology, crop yields, and environmental sustainability metrics at finer levels of detail. Figure 8 includes an aerial photograph and the spatial distribution of simulated maize and teff yields for the unirrigated, low-nitrogen Baseline displayed for the 90m x 90m land use/land cover pixels within a small portion of the Weg-Arba Amba kebele.

Figure 8 illustrates several important strengths and limitations of these models and the spatial databases they use. First, the fine detail of high and low crop yields (or other outputs like soil erosion) can provide valuable information about areas within the kebele where more intensive cropping systems or conservation practices should be implemented. For this analysis the specific locations of croplands, specific crops, and areas without crops were obtained from Ethiopian sources. In addition, rules were developed to determine whether continuous crops or crop rotations were grown on specific 90m x 90m land use/land cover pixels. SWAT then simulated the growth and yields of the assigned crops for each 90 m x 90 m pixel.

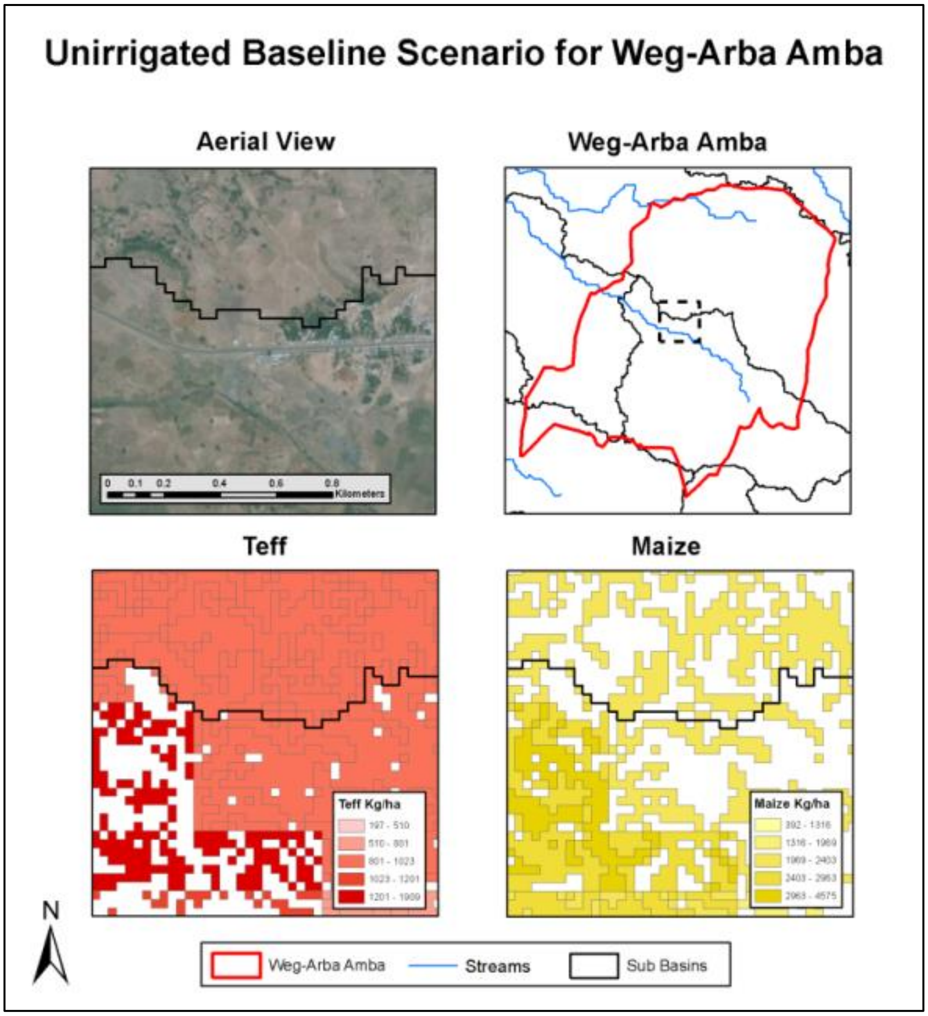

Figure 8. Spatial variation in mean maize and teff yields for the Baseline (irrigated, low nitrogen fertilizer) scenario in a small area of the Weg-Arba Amba kebele.

As is evident from Figure 8, the simulated yields of some pixels were greater than others, largely due to differences in soil properties such as soil slope, water holding capacity, organic matter, and depth. Appendix 5 gives similar resolution data for the Weg-Arba Amba kebele as well as more intensive cropping systems for both kebele.

Both SWAT and APEX can be used to generate this type of spatially detailed output for production and environmental sustainability metrics like those illustrated in Figures 3, 4, and 8. This capability can reliably inform *ex ante* assessments of the likely food production and environmental impacts of BMGF projects in Africa, South Asia, and other areas of interest to the Foundation (see Appendix 7).

Economic and Nutrition Analyses

Data and Model

A farm level Monte Carlo simulation model, FARMSIM, was used to perform an economic and nutrition analysis for the two study regions. Two representative “farms” (kebele) were simulated for the base and two alternative technology farming systems or scenarios. (A detailed description of FARMSIM is provided in Appendix 8.) The FARMSIM model simulates a representative farm for five years (2013-2017) using stochastic market prices, crop yields, and livestock production values. The model is recursive in that the financial values at the end of 2013 are the beginning financial values for the start of 2014. Cattle, sheep, goats, and chickens are included in the model and their numbers are simulated over time based on parameters for fractions of animals consumed, die, culled, and stochastic birthrates.

Data to simulate farms in the two kebele were provided by Mr. Abeyou Wale, IWMI/Ethiopia, and Ethiopian colleagues from the Amahara Region. Due to the aggregation problems with simulating a single, small-holder farm, the aggregate data for the kebele were used to describe and simulate each kebele as a representative farm. The basic information about the two farms is summarized in Table 4. The Shena farm represents the 2,071 hectares of cropland and 2,151 families for the kebele. The Weg-Arba Amba farm represents 1,514 families and 3,640 hectares of cropland. More detailed information to describe the two farms is provided in Appendix 6.

Table 4. Characteristics for Shena and Weg-Arba Amba Farms.

	Shena	Weg-Arba Amba
Number of Families	2,151	1,514
Cropland (HA)	2,071	3,640
Crops		
Miaze (HA)	1,800	914
Rice (HA)	2,071	-
Onions (HA)	1,800	-
Teff (HA)	-	2,710
Cows	4,174	1,893
Oxen	4,611	1,788
Hens	6,000	3,020
Ewes	700	150
Nannies	-	1,853

Linkage Between FARMSIM and APEX

The APEX model was simulated for 32 years using local weather data for 1979-2010 for each farming system to estimate crop yields under alternative weather conditions. The resulting 32 simulated grain and forage yields provide data necessary for FARMSIM to estimate probability distributions (PDFs) for yield, as yield is a stochastic variable in the economic model. Stochastic annual yields for crops and forage in FARMSIM were simulated as multivariate empirical

(MVE) PDFs maintaining the observed correlation for the stochastic yields generated by APEX. Three MVE PDF's were developed for each farm as different yield distributions were used for each scenario/farming system.

Technology Adoption Assumption

The literature on technology indicates that the rate of adoption varies widely for alternative technologies. For the current analysis it was assumed that the farming systems interventions are adopted at the rate of 25% and this adoption rate is constant throughout the planning horizon. The model is capable of simulating any assumed adoption curve where the rate of adoption changes each year, such as, 5%, 10%, 15%, 20% and 25% over the 5 year planning horizon. To test the sensitivity of the adoption rate assumption the Baseline+N farming system was also simulated using a 50% adoption rate.

Economic and Nutritional Impacts -- Weg-Arba Amba

The changes in economic benefits to the Weg-Arba Amba kebele for alternative farming systems are reported in Table 4. The Weg-Arba Amba kebele is non-irrigated in the Baseline case and has a 9,643 Birr average annual net cash farm income (NCFI) per family (Table 5). For the Baseline+N scenario NCFI averages 21,063 Birr and for the Baseline+N+V scenario the value is 22,207 Birr. The increases in NCFI are due to higher grain and associated forage yields. Increased forage yields and reduced yield risk lead to increased livestock production, receipts and net cash income. Average per family net cash income generated by livestock increased 24% for the Baseline+N cropping system and 26% for the Baseline+N+V system. Average ending cash reserves in 2017 are projected to increase from 22,803 Birr in the Baseline to 92,749 Birr for the Baseline+N+V scenario.

Table 5. Economic and nutrition impacts of alternative farming systems for the Weg-Arba Amba kebele.

	Baseline	Baseline+N	Baseline+N+V
	(Birr)	(Birr)	(Birr)
Average Values per Family in Year 5			
Net Present Value	111,007	142,552	153,308
Average Net Cash Farm Income	9,643	21,063	22,207
Average Crop Net Income	8,303	19,396	20,514
Average Livestock Net Income	1,340	1,666	1,693
Average Ending Cash Reserves	22,803	82,695	92,749
Average Daily Nutrient per Adult			
Energy (calories/day)	2,143	2,212	2,345
Protien (grams/day)	60.5	60.0	62.9
Fat (grams/day)	37.6	39.7	41.1
Calcium (grams/day)	0.2537	0.2167	0.2296
Iron (grams/day)	0.0190	0.0180	0.0191
Vitamin A (grams/day)	0.0012	0.0012	0.0012

The nutritional benefits from improved yields and higher average annual NCFI per family are observed in terms of increased average daily consumption of energy, protein, fat, calcium, iron and vitamin A (Table 5). The Baseline+N+V scenario leads to a 9.4% increase in average daily consumption of energy (calories) for a family in the Weg-Arba Amba kebele. A summary of the nutritional requirements of an adult equivalent and the assumptions used in FARMSIM for nutrition is provided in Appendix 9. FARMSIM uses the OECD definition of an AE which represents a weighted aggregation of a family unit's consumption. An AE counts the first adult as 1 and each additional adult at 0.7 and counts children under 15 at 0.5.

The stochastic capabilities of FARMSIM provide probabilistic results for the output variables. The alternative farming systems shift the NCFI probability distribution to the right which significantly reduces the chance of low average annual NCFI per family (Figure 9). The Baseline+N+V NCFI distribution has a slightly higher mean but has a larger standard deviation and thus more risk than the Baseline+N alternative.

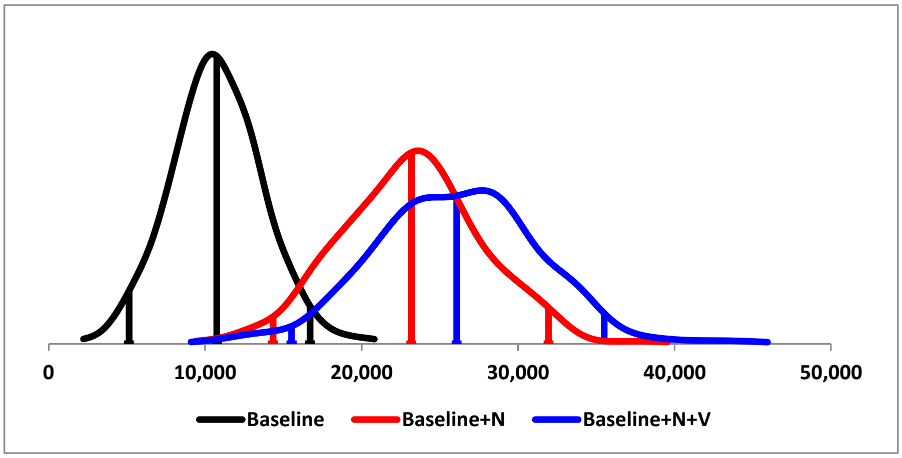

Figure 9. Probability density functions for family NCFI on a Weg-Arba Amba farm, assuming alternative farming systems.

The StopLight chart in Figure 10 summarizes the risk on NCFI depicted in the PDFs in Figure 9. The StopLight chart shows that there is a 39% chance annual NCFI is less than 10,000 Birr for the Baseline case (Figure 10). For the Baseline+N scenario the probability of annual NCFI being below 10,000 Birr is zero and there is an 32% chance that annual NCFI is greater than 25,000 Birr. Under the high technology scenario the probability of annual NCFI exceeding 25,000 Birr is 57% and there is a 43% chance NCFI is between 10,000 Birr and 25,000 Birr.

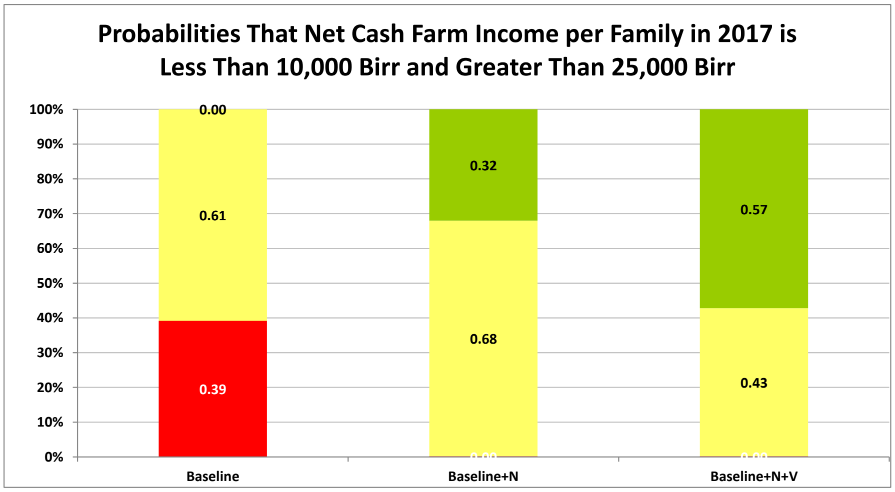

Figure 10. StopLight chart for family NCFI on a Weg-Arba Amba farm from crops and livestock, assuming alternative farming systems.

Net cash income from livestock is improved by the two interventions, although they are primarily aimed at improving crop yields. The Stoplight chart in Figure 11 indicates that under the Baseline the family's farm income from livestock has an 11% chance of being less than 500 Birr. For the two interventions the probability of livestock income being less than 500 Birr is zero and the probability that this value is greater than 1,500 Birr is greater than 75%.

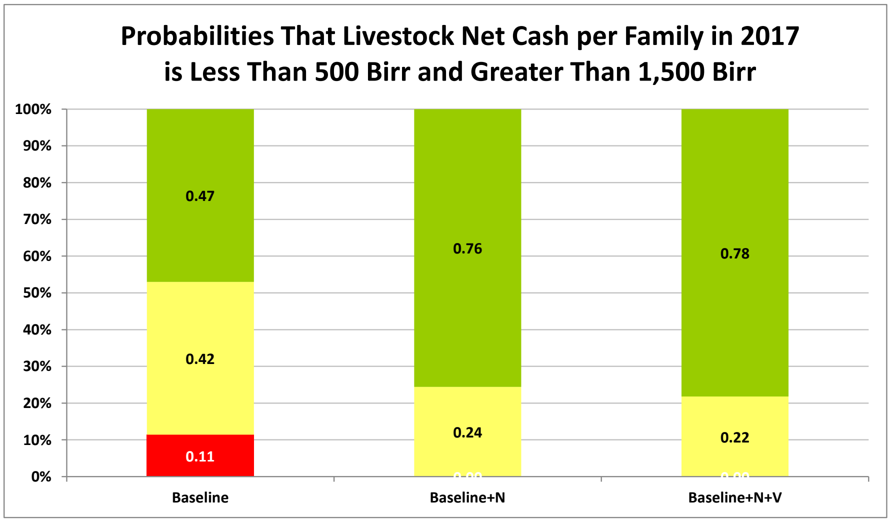

Figure 11.StopLight chart for family NCFI derived from livestock, assuming alternative farming systems.

Increases in NCFI benefit the kebele by increasing the cash available. The StopLight chart in Figure 12 summarizes the probabilities that ending cash reserves in 2017 for a family are less than 20,000 Birr and greater than 90,000 Birr. The Baseline has a 34% chance that ending cash reserves for a family will be less than 20,000 Birr and a 66% chance of being greater than 90,000

Birr. The Baseline+N+V intervention give a family a 61% chance of ending cash in 2017 exceeding 90,000 Birr.

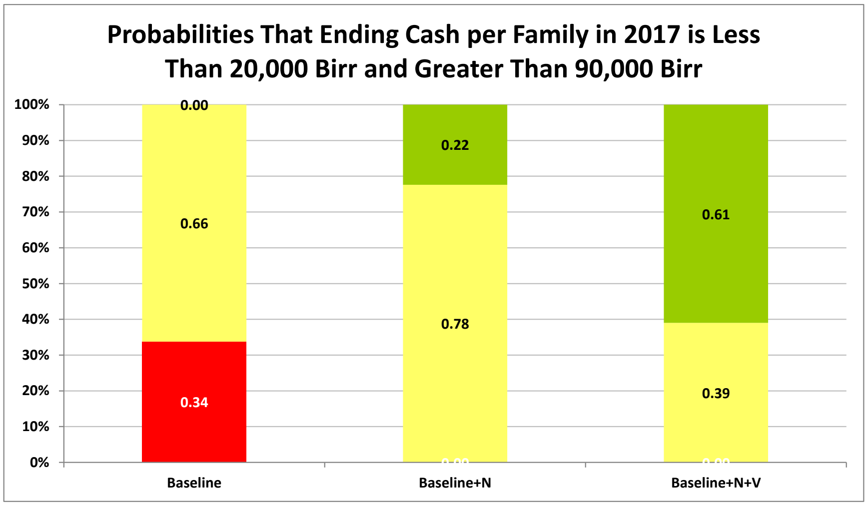

Figure 12. StopLight chart for per ending cash reserves in 2017, assuming alternative farming systems.

The StopLight chart for daily energy consumption per adult equivalent (AE) is presented in Figure 13. Introduction of irrigation and proper fertilization (Baseline+N) decreases the probability that daily energy consumption is less than 1,900 calories per AE from 11% to zero. Similarly, the daily consumption of protein, fat, calcium, iron and vitamin A increases as yields improve with the alternative farming systems. StopLight charts for daily consumption of other nutrients across the three interventions are presented in Appendix 10.

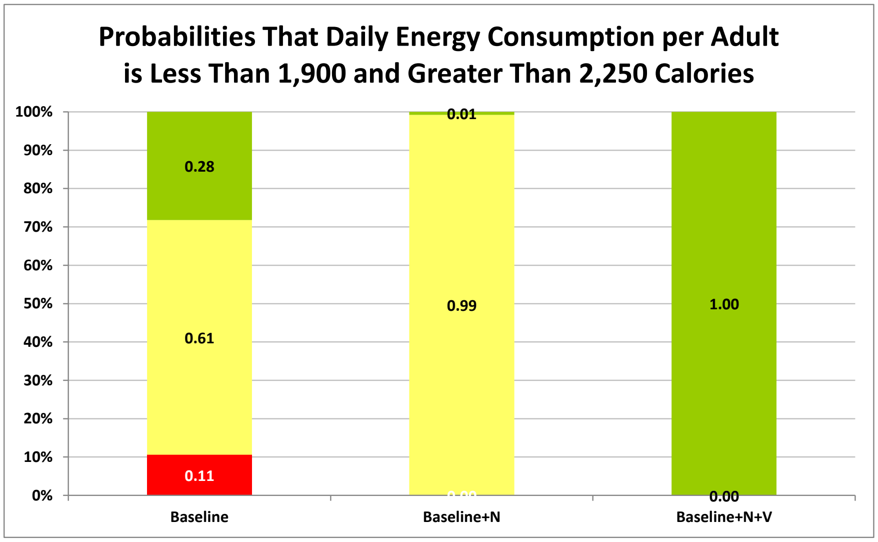

Figure 13. StopLight chart for daily energy consumption per adult equivalent on a Weg-Arba Amba farm for alternative farming systems.

The Baseline+N scenario was simulated a second time for the Weg-Arba Amba kebele assuming a 50% rate of adoption (Table 6). Increasing the rate of adoption significantly improves the financial viability of a family in the Weg-Arba Amba kebele. Average family NCFI increases from 21,063 Birr to 33,921 Birr (Table 6) and as indicated in Figure 14 the increased adoption rate significantly shifts the entire NCFI probability distribution to the right. Increasing the adoption rate improves average livestock net income 47.5% and ending cash reserves 76%. Nutrition for a family improves based on average consumption of six nutrients tracked in FARMSIM.

Table 6. Comparison of assuming 25% vs. 50% adoption rates for the Baseline+N farming system.

	Baseline+N 25%	Baseline+N 50%
	(Birr)	(Birr)
Average Values per Family in Year 5		
Net Present Value	142,552	189,205
Average Net Cash Farm Income	21,063	33,921
Average Crop Net Income	19,396	31,464
Average Livestock Net Income	1,666	2,457
Average Ending Cash Reserves	82,695	145,572
Average Daily Nutrient per Adult		
Energy (calories/day)	2,212	2,277
Protien (grams/day)	60	62
Fat (grams/day)	40	42
Calcium (grams/day)	0.2167	0.2531
Iron (grams/day)	0.0180	0.0188
Vitamin A (grams/day)	0.0012	0.0012

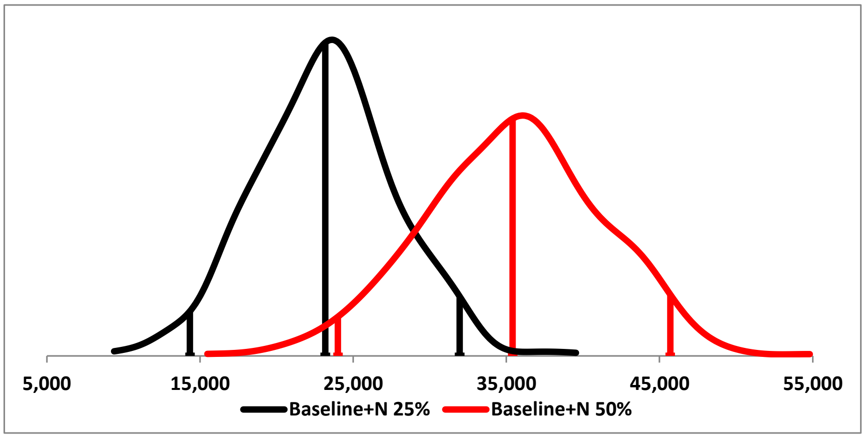

Figure 14. Comparison of probability distributions for family NCFI in the Weg-Arba Amba kebele assuming 25% vs. 50% adoption rates for the Baseline+N scenario.

Economic and Nutritional Impacts – Shena

Average annual NCFI per family under the Baseline is estimated at 19,047 Birr for the Shena kebele (Table 7). By optimizing crop production under the Baseline+N scenario average annual NCFI is increased to 25,547 Birr (assuming a 25% adoption rate) and under the high tech scenario (Baseline+N+V) the average annual NCFI is 28,530 Birr. The increases in NCFI are due to higher maize, rice, and onion yields and their associated forage yields. Increased forage yields and reduced yield risk lead to increased livestock production and receipts.

Table 7. Economic and nutrition impacts of alternative farming systems for the Shena kebele.

	Baseline	Baseline+N	Baseline+N+V
	(Birr)	(Birr)	(Birr)
Average Values per Family in Year 5			
Net Present Value	135,993	161,736	177,943
Average Net Cash Farm Income	19,047	25,547	28,530
Average Crop Net Income	18,118	24,502	27,485
Average Livestock Net Income	929	1,045	1,045
Average Ending Cash Reserves	68,021	76,042	98,194
Average Daily Nutrient per Adult			
Energy (calories/day)	1,913	2,001	2,097
Protien (grams/day)	59	60	62
Fat (grams/day)	38	40	41
Calcium (grams/day)	0.3335	0.3393	0.3406
Iron (grams/day)	0.0173	0.0178	0.0184
Vitamin A (grams/day)	0.0016	0.0016	0.0016

The probability distributions for NCFI under the Baseline and the two interventions are reported in Figure 15. The probability density functions show that NCFI has a great deal of risk, ranging from -5,000 Birr to a maximum of about 20,000 under the Baseline. The interventions significantly shift the maximum NCFI to the right increasing the maximum to more than 50,000 Birr but increasing the minimum only slightly. On net the interventions increase the mean NCFIs over the Baseline.

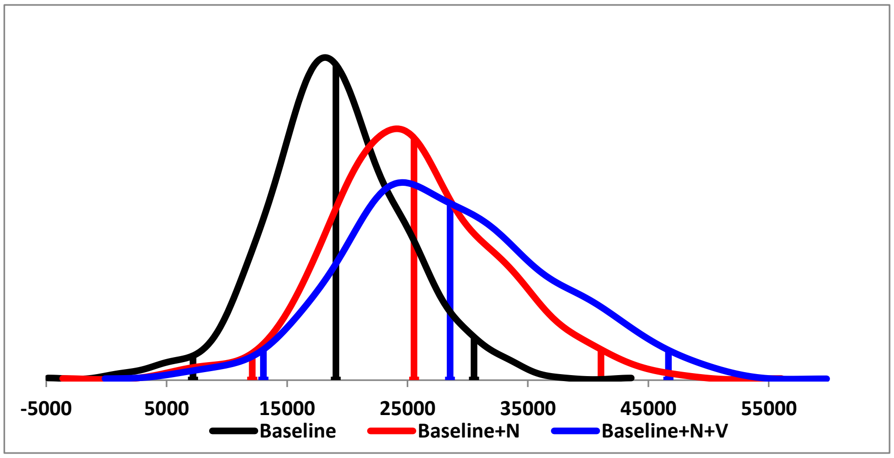

Figure 15. Probability density functions for family NCFI in the Shena kebele, assuming alternative farming systems.

The NCFI probability distributions depicted in Figure 15 are presented in terms of StopLight charts in Figure 16. Under the Baseline a family has a 2% probability that NCFI will be less than 5,000 Birr and a 14% chance that NCFI will exceed 25,000 Birr. A 25% adoption of the Baseline+N intervention reduces the probability of NCFI less than 5,000 Birr to zero and increases the probability of NCFI exceeding 25,000 Birr to 51%. The Baseline+N+V intervention is even more favorable for NCFI with a 62% chance that NCFI will exceed 15,000 Birr.

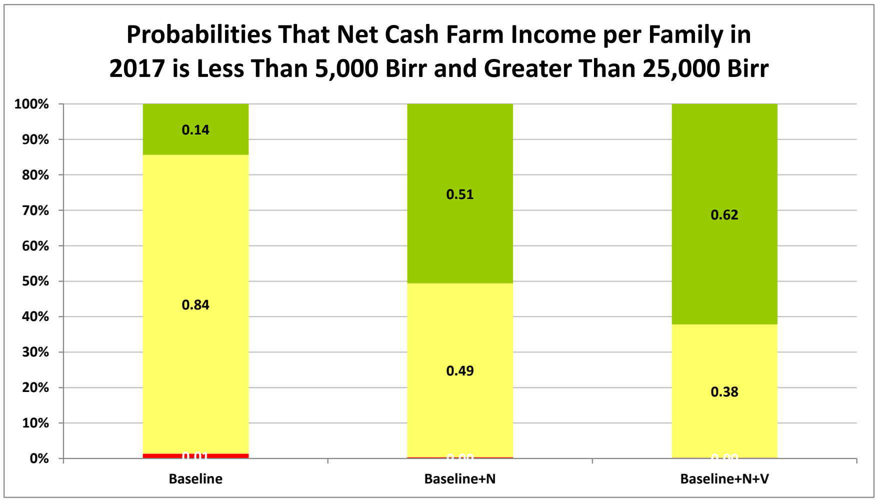

Figure 16. StopLight chart for per family NCFI on a Shena farm assuming alternative farming systems.

Increased crop yields will provide greater yields of forage for livestock. Average net cash income for livestock is projected to increase 12.5% from the Baseline to the two interventions (Table 7). The StopLight chart for livestock net cash income shows that the Baseline has a 30% chance of livestock net income for a family being less than 800 Birr per family and only a 22% chance that livestock net income will exceed 1,200 Birr (Figure 17). The interventions reduce the probability that net cash income from livestock will be less than 800 Birr to 9%.

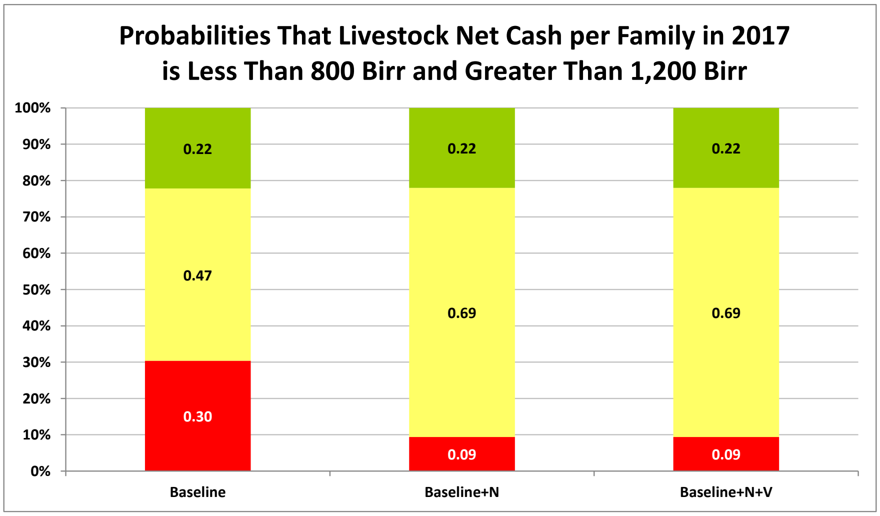

Figure 17. StopLight chart for family NCI from livestock in the Shena kebele assuming alternative farming systems.

Increasing family NCFIs leads to increased ending year cash reserves in 2017. Average ending cash reserves in 2017 are 68,021 under the Baseline and 76,042 Birr for the Baseline+N alternative (Table 7). These statistics are more meaningful when presented in terms of the probabilities that ending cash reserves will exceed a minimum target. The StopLight chart in Figure 18 shows the probability that a family's ending cash reserve will be less than 50,000 Birr and greater than 100,000 Birr. With the Baseline+N+V farming system there is a 45% chance that ending cash reserves for a family would exceed 100,000 Birr while there is only a 1% chance of this outcome under the Baseline.

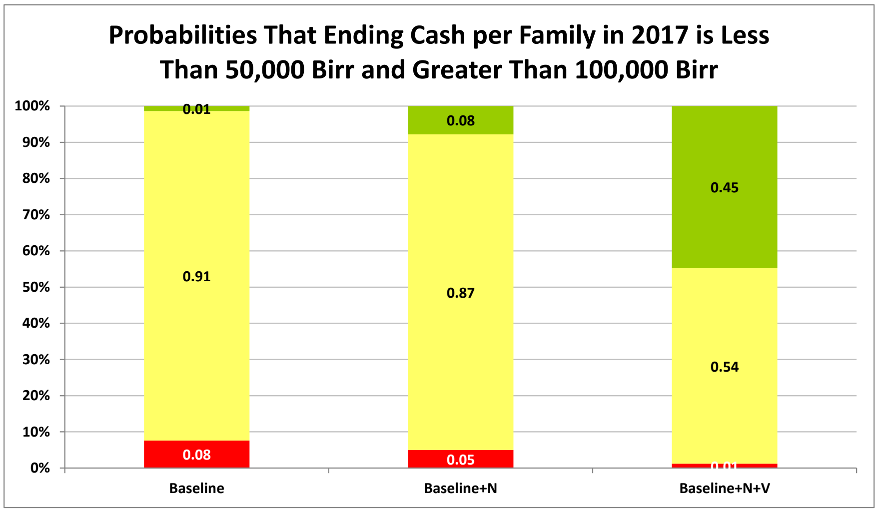

Figure 18. StopLight chart for per family ending cash reserves on a Shena farm assuming alternative farming systems.

Increased yields and revenue would allow the families to improve their diet, even when crop yields are low due to drought. The average daily consumption of calories for an adult equivalent (AE) is estimated at 1,913 calories for the Baseline, 2,001 for the Baseline+N and 2,097 for the Baseline+N+V scenario (Table 7). Similarly, the daily consumption of protein, fat, calcium, iron and vitamin A increases as yields improve with the alternative farming systems.

The StopLight chart for daily energy consumption per adult equivalent (AE) is presented in Figure 19. The introduction of improved production practices decreased the probability of energy deficiency in the diet. There is an 11% chance that energy consumption per AE is less than 1,850 calories per day for the Baseline, and a zero probability of energy consumption less than this target value for the Baseline+N and Baseline+N+V scenarios. Although stated as AE, the probable deficiency would likely have most serious consequences for the physical and cognitive development of children in family. The Baseline+N scenario actually provides a 100% chance that average daily energy consumption per AE will be between 1,850 and 2,100 calories. The daily consumption of protein, fat, calcium, iron and vitamin A increases as yields improve with the alternative farming systems. StopLight charts for daily consumption of other nutrients across the three interventions are presented in Appendix 10.

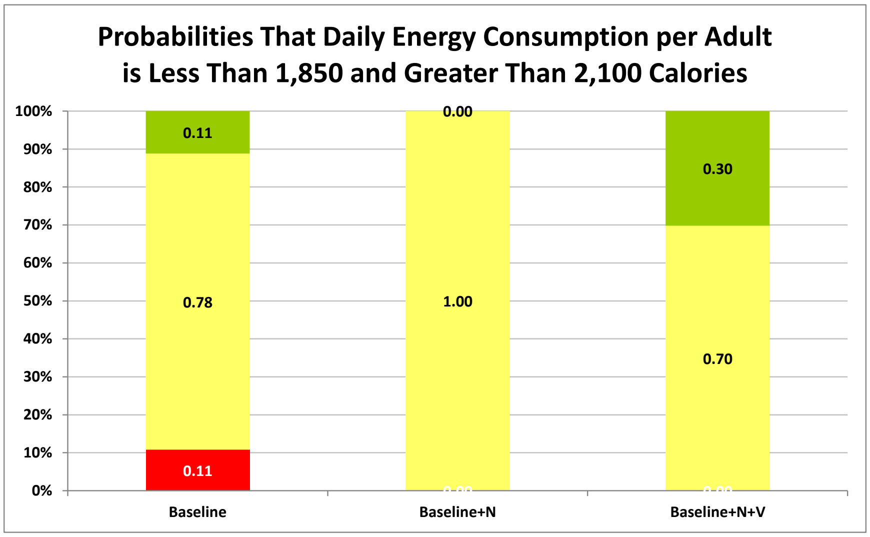

Figure 19. StopLight Chart for daily energy consumption per adult equivalent on a Shena farm assuming alternative farming systems.

The Baseline+N scenario was simulated a second time for the Shena kebele assuming a 50% rate of adoption (Table 8). Increasing the rate of adoption significantly improves the financial viability of a family in the Shena kebele. Average family NCFI increases from 25,547 Birr to 33,863 Birr (Table 8) and as indicated in Figure 20 the increased adoption rate significantly shifts the entire NCFI probability distribution to the right. Increasing the adoption rate improves average livestock net income 3% and ending cash reserves 55%. Nutrition for a family improves slightly based on average consumption of six nutrients tracked in FARMSIM. Average family nutrition improvements are small, because the families in the Shena kebele are consuming more than the average daily minimum requirements for most all nutrients, even under the Baseline. Producing additional quantities of maize, rice, and onions are assumed to increase consumption slightly but are primarily used to increase receipts and NCFI.

Table 8. Comparison of assuming 25% vs. 50% adoption rates for the Baseline+N scenario.

	Baseline+N 25%	Baseline+N 50%
	(Birr)	(Birr)
Average Values per Family in Year 5		
Net Present Value	161,736	187,935
Average Net Cash Farm Income	25,547	33,863
Average Crop Net Income	24,502	32,791
Average Livestock Net Income	1,045	1,072
Average Ending Cash Reserves	76,042	117,736
Average Daily Nutrient per Adult		
Energy (calories/day)	2,001	2,003
Protien (grams/day)	60	60
Fat (grams/day)	40	40
Calcium (grams/day)	0.3393	0.3409
Iron (grams/day)	0.0178	0.0178
Vitamin A (grams/day)	0.0016	0.0016

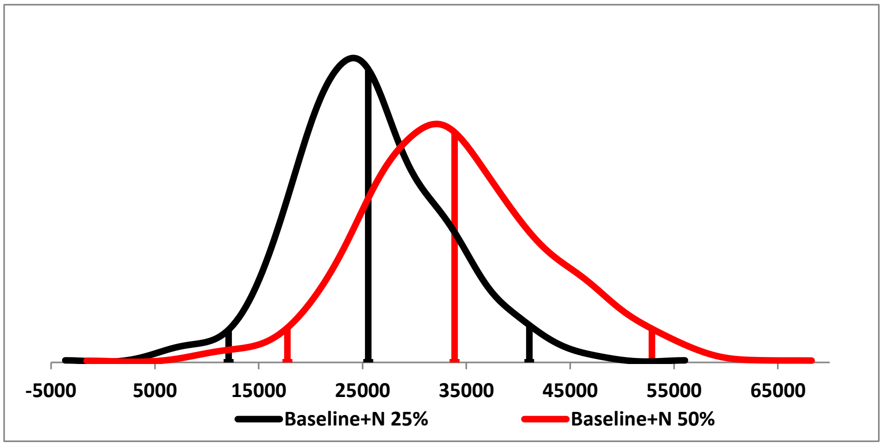

Figure 20. Probability density functions for family NCFI in the Shena kebele, assuming alternative adoption rates for the Baseline+N farming system.

Summary of Farm Level Analysis

Introduction of optimal plant fertilization and irrigation has the potential for greatly improving net income and nutritional intake for small-holder farmers in the Shena and Weg-Arba Amba kebele. Greater benefits will be observed for the Weg-Arba Amba farms because these farms are presently non-irrigated; average family NCFI increases 218% from 9,643 to 21,063 Birr per year.

The Shena farms are presently irrigated but still see a significant increase in net income (12%) by optimizing their plant nutrition program.

Improvements in farming systems lead to an increase in daily intake of nutrients for an AE. The nutritional improvements are smaller than the income increases because the kebele are producing adequate levels of grain and families are consuming adequate levels of nutrients in the Baseline case. Additionally, during years of low yields adequate cash should be available in the Baseline case to purchase food to meet current desired levels of consumption. Prolonged droughts would pose a significant problem because cash reserves would be reduced to zero after the first few years of drought.

Economic Impacts for the Lake Tana Basin Watershed

The economic impacts to the watershed analyzed with SWAT for the alternative farming systems are projected based on the per hectare average annual net cash farm income projected for the representative farms and the number of hectares of land with similar slope in the watershed. The watershed used for the analysis contains the Gumera and Rib river basins. The watershed has about 8,000 hectares of cropland similar to the less than 10% slope land in the Shena kebele. It is estimated that 750,000 hectares of cropland which can be potentially irrigated in the watershed has from 10% to 20% slope like the maize/teff land in the Weg-Arba Amba kebele. Scaling up the average annual NCFI for the watershed, based on hectares in the two kebeles, projected NCFI per hectare, and number of similar cropland hectares is not ideal but it gives a gross estimate of the economic impacts to the watershed.

The annual economic impacts assuming 25% adoption of the Baseline+N farming system for farmland with less than 10% slope is expected to be an net gain in NCFI of 27.6 million Birr and for adoption of the Baseline+N+V farming system is an expected increase in NCFI of 54 million Birr (Table 9). The NCFI for the steeper sloped land is projected to increase from 3.0 billion Birr to 6.5 billion Birr (gain of 3.5 million) if the Baseline+N farming system is adopted at a rate of 25%. The economic impact for the steeper farmland is much greater even though the Birr/hectare NCFI is lower on the steeper land because of the greater number of hectares of steeper land (750,000 vs. 8,000). If the Baseline+N intervention had widespread adoption in a short period, there would most likely be a negative price impact which would decrease these estimated increases in NCFI. However, given a more normal adoption process the price effects will be much smaller as markets and population adjust to improved quantity and quality of food.

Table 9. Economic benefits to the watershed from adoption of alternative farming systems.

Crop Rotation and Slope	Hectares	Average Annual Net Cash Farm Income Baseline	Baseline+N	Baseline+N+V
			(1,000 Birr)	
Onions/Corn/Rice; fields <10% slope	8,000	158,262	212,271	237,057
Change from Base			134%	150%
Corn/Teff; fields 10-20% slope	750,000	3,008,139	6,570,614	6,927,486
Change from Base			218%	230%

Summary of Mission to Ethiopia

As a result of guidance from the Gates Foundation administrators for this contract, the Texas A&M mission to Ethiopia was undertaken to seek engagement and advice from national and international stakeholders relative to the validity, utility, and sustainability of the Integrated Decision Support System, the results of which were presented to the Gates Foundation leadership and staff in January 2013. Key issues included determining if there is a useful role for the IDSS in the development agendas of government agencies; exploring how the requisite input data for the IDSS might be obtained in Ethiopia and other developing countries, and to explore how the IDSS might be woven into the fabric of the agendas for planning and implementation of technology and policy to achieve the goals of Ethiopia's Agricultural Growth Plan and thereby help ensure its longer term sustainability.

As a result of evaluation of the initial report on the pilot study in January, a second work order was initiated to further engage stakeholders in Ethiopia to extend the evaluation of the methodology. The first and second work orders overlap slightly in time and purpose. Work Order #1, covers the initial development of the pilot study and included a task for seeking feedback from Ethiopian experts on the system. The more detailed evaluation of the IDSS in terms of its application in Ethiopia and other SSAs is funded in the second work order. This section of the report on Work Order #1 focuses on the evaluation of the IDSS methodology by counterparts in Ethiopia. The development of more detailed approaches for possible integration of the IDSS into ongoing and planned programs in Ethiopia and beyond will be reported under Work Order #2.

Senior administrators and experts from the Ethiopian Ministry of Agriculture (MOA) and the Ethiopian Agricultural Transformation Agency met with the IDSS team where seminars on the IDSS were followed by active discussion aimed at evaluating the system and pursuing how it might be used in various agencies. At both the leadership and expert levels, the capabilities of IDSS as indicated in the pilot study appeared to be both reasonable and relevant to ongoing and planned development activities in Ethiopia. IDSS methodology was recognized as adding a useful dimension to ongoing studies, especially regarding the ability to provide an overall integrated assessment of impact of alternative investment decisions and to evaluate t results of ongoing or recently completed development projects.

There was broad interest in using the IDSS with multiple specific opportunities identified for its incorporation into new and planned development in both the MOA and ATA. Leadership in both agencies will communicate their interest in collaborating with TAMU in strengthening and using IDSS in Ethiopia if a Gates Foundation grant to further develop and demonstrate its use is provided. At the level of the State Minister of Agriculture, there is active interest in the early application of the IDSS to the Planning Directorate and strategic assessment of options for development and training. In the Agriculture Transformation Agency initial interest is in applying the IDSS to their ongoing development activities at the Woreda Cluster level, taking the application of the system to the enterprise level. Training will be a critical component of the early efforts for both the Ministry and the ADA. Multidisciplinary teams of experts would be trained to use the suite of models and to train others to use them. Texas A&M, would work with national partners to develop, evaluate, train, and backstop national experts in the use of the IDSS for their programs.

The CGIAR centers with presence at the ILRI/Addis Campus (ILRI, IWMI, ICARDA, CIMMYT) were also engaged and all found that the IDSS could add a useful analytic capacity in both CGIAR Research Programs and System Initiatives. Initial discussions of how to develop a structure and platform for multi-center engagement of the IDSS provided an initial pathway towards cooperation and collaboration. With further demonstration and site specific application, the IARC leadership and faculty believe the IDSS can be a useful analytic tool added to their existing methods to more effectively and comprehensively conduct ex ante and ex post assessment of the integrated impact of options for introduction of technology or policy in developing country scenarios. Leaders of the several centers are also willing to communicate with the Gates Foundation in support of funding for the further development and integration of the IDSS into the analytic framework of the centers.

The positive reaction to the methodology and results in the pilot study by all of our contacts in Ethiopia provided good support for the validity and relevance of the methodology and its potential use in the country and in SSA. Reviewers believed that the IDSS could provide an important new dimension to their planning and evaluation procedures and that the methods could be incorporated and used in their programs. There was active interest by the Government of Ethiopia institutions in partnering with a Gates sponsored effort to develop applications for the IDSS in their ongoing and planned programs in Ethiopia. Similar interest in collaboration exists among several CGIAR centers to use the IDSS in Ethiopia and more broadly in SSA. Based on these interests, a working paradigm emerged which addresses some of the key issues related to the utility and sustainability of the IDSS. In general terms, the emerging strategy is to use the

IDSS as a component part of the overall methodology in strategic planning at the Ministry of Agriculture for implementing the Agricultural Growth Program and to use the system to facilitate planning and evaluation of the Agricultural Transformation Agency development thrusts at the Woreda Cluster level in several of the more productive areas of the country. By incorporating the IDSS into the ongoing programs in country and training teams of experts to use it in their analyses with backstopping by the Texas A&M team, two major issues are addressed. First, the acquisition of data at local and national levels is enhanced by the partnership where existing and ongoing engagements will use national experienced experts to acquire and interpret the detailed information needed to run the IDSS on their programs at varying levels of scale. Second, by incorporating the IDSS into ongoing programs in both the Ethiopian and International Center programs and providing early national team training for the use of the system, a major step will be taken in assuring the long term sustainability of the effort past the duration of a possible Gates grant. Further details and planning resulting from this mission are reported under Work Order #2.

The schedule and contacts for this mission are contained in appendix 11. This appendix also contains an aide memoire which specifically summarizes the engagements and resulting actions from meetings with various stakeholders.

Summary, Conclusions, and Recommendations

This pilot study demonstrates the ability of the IDSS to provide an integrated assessment of the impact of introduction of new technology at the farm/village and watershed levels of scale. Regions that are important agriculturally to a country were selected and analyzed from the big picture of a watershed down to the representative farm in two kebeles. The results from the SWAT model were integrated into the APEX plant growth model and its yield distributions for alternative cropping interventions were used as input to the farm level economic and nutritional impacts analysis. Results of the analysis show the significant improvements in family incomes that can be had through the adoption of irrigation, proper use of fertilizer, and improved seed varieties; while improving the environmental indicators of soil erosion and sediment loadings.

Because of the limited scope of this study, databases used in the analysis were taken from available sources and expert opinions and could be more precise if greater accuracy were needed in the actual application of the IDSS to a specific task. Likewise, this demonstration did not consider a variety of related issues such as roads and markets and other infrastructure, training and education, and enabling policies that might be required to bring the proposed interventions to practice. To make the output more realistic, a 25% adoption rate was assumed for the economic outputs and was compared to a 50% adoption rate to show the sensitivity of this variable on the outcomes.

Even with conservative estimates of adoption, the results of the interventions were positive. The results of these simulations were not intended to fully define the results of the interventions but to show the ability of the IDSS to produce results that reasonably compare the impact of examples of new technologies and to showcase the diversity of analytic products that can be brought to bear on our analyses at multiple levels of scale. The next step in this demonstration will be a further assessment of the utility of the IDSS methodology and results by experienced national scientists and managers to help evaluate the validity, sustainability, and utility of the IDSS and its component parts in planned or ongoing interventions and applications for Ethiopia. The IDSS model components can readily accommodate these expert opinions as inputs to succeeding iterations of outcomes. In the broader strategy, the IDSS could be further developed and validated at watershed, regional and national levels in Ethiopia in preparation for its use more broadly in Sub-Saharan Africa and South Asia.

These pilot studies demonstrate that the IDSS can be a useful addition to the methods used by the Foundation to predict and evaluate the consequences of various interventions to improve the livelihoods of subsistence farmers while evaluating the environmental consequences at multiple levels of scale. The results demonstrate the ability to predict the outcomes of interventions using quantitative stochastic methods. The IDSS provides an integrated systems approach to assessment of new investment options, including analysis of water use and protection as a transcending factor in successful development of methods to feed future populations. The ability to *concurrently* assess production, environmental, and economic and nutritional consequences of options for sustainable increases in production of food and use of scarce natural resources using an *integrated* modeling approach adds *unique* value to the Gates Foundation portfolio of analytic tools.

The mission to Ethiopia to present the results of the pilot study provided positive responses regarding the potential utility of the IDSS and interest in incorporating the system into ongoing and planned analyses in the Ministry of Agriculture and the Agricultural Transformation Agency.

The IDSS could have application to the *ex ante* strategic planning of future investments by the Foundation by commodity and geographic location. The same set of tools could be used throughout the development cycle to select projects for initial funding, evaluate progress towards meeting explicitly stated goals, and to provide assessment of final results in terms of outcomes and information for future actions. It offers the ability to predict where the results of research done in one location might guide planning to its application to other geographically equivalent national or transnational sites. The IDSS provides the information needed by government and private sector investors to quantitatively assess the integrated impact of new technology or policy based interventions for future actions.

These early pilot studies used interventions that are optimized to enhance the sustainable production of food under the conditions of the two locations and their related watersheds. As a demonstration, the pilot study successfully exercised the suite of models in the IDSS to show their functionality. The results were consistent with historical experience for the baseline situations at both the kebele and watershed levels. The pilot study was not intended to analyze a specific set of actual scenarios. That is the goal of the next iteration of this project and would be done in close collaboration with national and international partners. The selection of the two sites was made to assure a reasonable access to markets and to compare different opportunities for the introduction of irrigation methods. Recognizing the longer term investment of the Foundation in modern crop germplasm, the second intervention adds the assumption that new crop germplasm was successfully introduced. Clearly, the successful introduction of the new farming practices and technologies would require substantial development of infrastructure such as roads and marketing support, supportive policy environments and active programs such as those now being undertaken in Ethiopia to train and motivate changes in social mores for adoption of new technologies. This pilot study includes the impact of traditionally low adoption rates, which might be enhanced by a more informed population. The IDSS offers the ability to evaluate the consequences of these enabling changes.

Appendices

Appendix 1 – History of Multi-Agency Natural Resource Modeling at Temple

Appendix 2 – Selection of Sites to Demonstrate the Integrated Decision Support System

Appendix 3 - Soil and Water Assessment Tool (SWAT) Applications for Africa

Appendix 4 – Comparative Capabilities of APEX and SWAT

Appendix 5 - SWAT Simulations for the Weg-Arba Amba and Shena Kebele

Appendix 6 – Simulation of Weg-Arba Amba and Shena Cropping Systems with APEX

Appendix 7 - IDSS Metrics for the Gates Environmental Sustainability Questionnaire

Appendix 8 - Farm Scale Nutrition and Economic Assessment Model: FARMSIM

Appendix 9 - Nutritional Requirements per Adult Equivalent

Appendix 10 - Farm Scale Nutritional and Economic Impacts of Alternative Farming Systems

Appendix 11 – Mission to Ethiopia