Ex Ante Analysis of Small-Scale Irrigation Interventions in Lemo

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Interpretive Summary

This report is part of the product of the USAID Feed the Future Innovation Laboratory for Small Scale Irrigation (ILSSI), and summarizes ILSSI's analysis of proposed small-scale irrigation (SSI) interventions in Lemo woreda, in the Southern Nations, Nationalities and Peoples (SNNP) region of Ethiopia. Farm-family livelihoods in the area are based on mixed crop and livestock production, with most farmers cultivating main crops of cereals and vegetables during the rainy season. During the dry season, most farmers use water from hand-dug, shallow wells for household use and to water livestock, with a few farmers irrigating tiny plots of land. Groundwater potential is relatively high; however, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

In Lemo, ILSSI proposed maximizing SSI of high-value, dry-season crops, using shallow groundwater and one of five alternative water-lifting technologies. ILSSI evaluated the proposed SSI interventions by simulating and comparing two alternative farming systems:

1. crop rotations of maize, teff and wheat, grown in the wet season, applying fertilizer at rates currently used by farmers in the region; and
2. crop rotations consisting of wet-season maize, teff, or wheat, fertilized at government-recommended rates, plus irrigated, dry-season double crops on all irrigable land (i.e., all areas with slopes less than 8%), using shallow groundwater.

Onion and fodder (oats/vetch) were chosen as representative dry-season crops for purposes of the simulations, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications.

Simulations indicated that there is great potential for increased SSI of dry-season crops in Lemo. A complete hydrologic analysis of the area's watershed (with a catchment area of 500 ha) calculated that the average annual volumetric groundwater recharge was over 1.5 million m^3, and that the proposed SSI interventions would use less than 10% of the annual shallow groundwater recharge. Excessive irrigation from shallow groundwater can deplete aquifers that contribute to stream flow, potentially reducing those flows; however, simulations indicated that the proposed SSI interventions would reduce average monthly stream flow by only 5.6% and should not compromise downstream flows. This suggests that the proposed SSI interventions can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage, and would not compromise the environmental health of the watershed.

As expected, simulations of the onion crop predicted that yields would increase substantially as applied irrigation water was increased up to 455 mm (the irrigation depth required to reduce plant stress levels to 0%). Similar results would be expected with respect to other dry-season crops, including fodder.

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping system) on farm-family economics in Upper Gana. These analyses compared the costs and benefits of five alternative water-lifting technologies: pulley-and-bucket irrigation, and rope-and-washer pumps operated by hand, animal, gasoline motor, and solar power. Of the alternate technologies examined, none of the technologies met the irrigation water requirements for the proposed SSI interventions (i.e., for all 540 ha of irrigable land in the kebele). Implementation of the proposed SSI interventions using gasoline motor pumps produced by far the highest NPV, NCI, and EC reserves of the six alternative scenarios simulated (including the baseline, non-irrigated scenario). The second-best-performing scenario implemented animal-powered pump irrigation, and the worst of the six scenarios simulated (including the baseline, non-irrigated scenario) was the scenario that implemented irrigation with pulley and bucket. In each of the alternative scenarios, the increase in farm revenue was due almost entirely to the sale of surplus irrigated fodder and onion. Where gasoline motor pumps were used, the forecasted sales of irrigated fodder and onion contributed, on average, 62% and 17%, respectively, of total crops receipts, and 83% and 17%, respectively, of the net cash (profit) for the five-year planning horizon.

Although gasoline-motor pumps could not irrigate all 540 ha of irrigable land in the kebele at 0% water stress, they had twice the coverage animal-powered pumps (the next-best alternative), though with much higher operational and capital costs. Individual farmers might benefit by spreading entry costs over more irrigated area, perhaps by having two or three farmers share a pump. Simulation results showed that irrigation with both gasoline motor pumps and animal-powered pumps will generate profit and income for the farmer. The lower operating, maintenance, and environmental costs of solar pumps (as opposed to gasoline-motor pumps) might also make them an attractive long-term option.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies persisted under the simulated, improved cropping system. We would also, therefore, propose expanding the types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits. The evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future study.

Introduction

There are three major components of ILSSI: (1) field studies evaluating selected SSI methods; (2) household surveys to assess the evaluate gender, nutrition, and economic consequences of SSI interventions; and (3) the application of a suite of integrated models to quantitatively estimate the impact of SSI on production, environmental, and economic outcomes. An iterative process of engagement is involved in linking the three components of ILSSI to form a final product.

The analyses summarized in this report contribute to the third ILSSI component: estimating the impacts of a proposed SSI intervention using the ILSSI's Integrated Decision Support System (IDSS). The IDSS is comprised of a suite of previously validated, interacting, and spatially explicit agroecosystem models: the Soil and Water Assessment Tool (SWAT), Agricultural Policy Environmental Extender (APEX), and Farm Scale Nutrition and Economic Risk Assessment Model (FARMSIM). The IDSS predicts short-term and long-term changes in crop and livestock production, farm economies, and environmental services produced by changing land uses, agricultural technologies and policies, climate, and water resources management, including SSI. The three models (and their sister and antecedent decision tools) have been used successfully for more than 25 years to address complex biophysical and economic issues in the United States and around the world. Designed to use readily available input data from global, national, and local sources, they can provide decision makers with reliable predictions of the production, environmental, and economic impacts of their actions.

The objective of this study was to use the IDSS to evaluate the benefits, environmental effects and economic viability of proposed SSI interventions on farms in Lemo, a woreda in the Hadiya zone of the SNNP region of Ethiopia. Upper Gana, a rural kebele located in Lemo, is located about 185 km from Addis Ababa. The region's climate is subtropical, and temperatures are ideal for cropping year-round, with a light rainy season from January to April and a main rainy season from June to August. About 75% of annual rainfall in the area occurs during the main rainy season. The dramatic shift in rainfall that occurs between wet and dry seasons restricts rain-fed cropping to the main rainy season. For double cropping, irrigation is needed in the dry season.

There are an estimated 1500 ha of cropland in Upper Gana, and about 130 ha of pastureland. The livelihoods of most residents are based on mixed crop and livestock production, though these patterns have been changing in response to various climatic, edaphic, socio-economic, and anthropogenic factors. Most farmers grow main crops of cereals and vegetables during the rainy season, and use water from hand-dug, shallow wells during the dry season, primarily for household use and to water livestock. A few farmers irrigate tiny plots of land (Langan 2014).

Rapidly increasing population, economic growth, and the movement of the rural population to cities provides a strong incentive for the Ethiopian government to help farmers increase production and farm-family nutritional and economic well-being. However, as in other parts of the world, farming systems in Ethiopia are complex and can have adverse environmental effects such as soil erosion, loss of plant nutrients, and changes in watershed hydrology. Increased reliance on small-scale irrigated agriculture, which is promoted by the government of Ethiopia, could have both positive effects on food production and negative effects on stream flows and shallow aquifers used for human and livestock water supplies. In addition, depending on equipment costs, labor availability, other crop input costs, and market prices of agricultural commodities, the increased use of SSI, or of specific irrigation technologies, may or may not prove economically beneficial.

Information about Lemo's natural resources, existing cropping systems, farm-family characteristics, and market conditions for agricultural products were obtained from a number of international, national, and local sources. These data were then used as inputs to the IDSS modeling system.

The baseline farming-system scenario simulated with FARMSIM, SWAT and APEX was the typical farming system currently used by farmers in the region. It consisted of traditional grains (maize, teff and wheat) grown as monocrops during the main rainy season, using shallow tillage with animal traction, and current fertilizer application rates. The proposed SSI interventions simulated with SWAT and APEX included the addition irrigated, dry-season, double crops in all irrigable cropland areas (irrigation-appropriate soils with slopes of less than 8%) within the 500-ha watershed. As noted above, onion and fodder (oats/vetch) were chosen as representative dry-season crops for purposes of the simulations, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications. Each irrigable crop (onion and fodder) occupied half of the 540 ha of irrigable cropland, and it was assumed that fodder was grown mainly for sale at market. In addition, APEX was used to simulate the effects of two alternate fertilizer rates on maize, teff and wheat, and one alternate fertilization rate on fodder, as well as seven irrigation amounts. FARMSIM was used to simulate the effects on farm-scale economics of various water-lifting technologies that could be used to implement the SSI interventions.

Parameterization, calibration, and execution of SWAT, APEX, and FARMSIM were closely coordinated, with input and output data exchanged in an integrated fashion to assure comparability of production, environmental, and economic results. This report describes the methodology, results, and implications of this study.

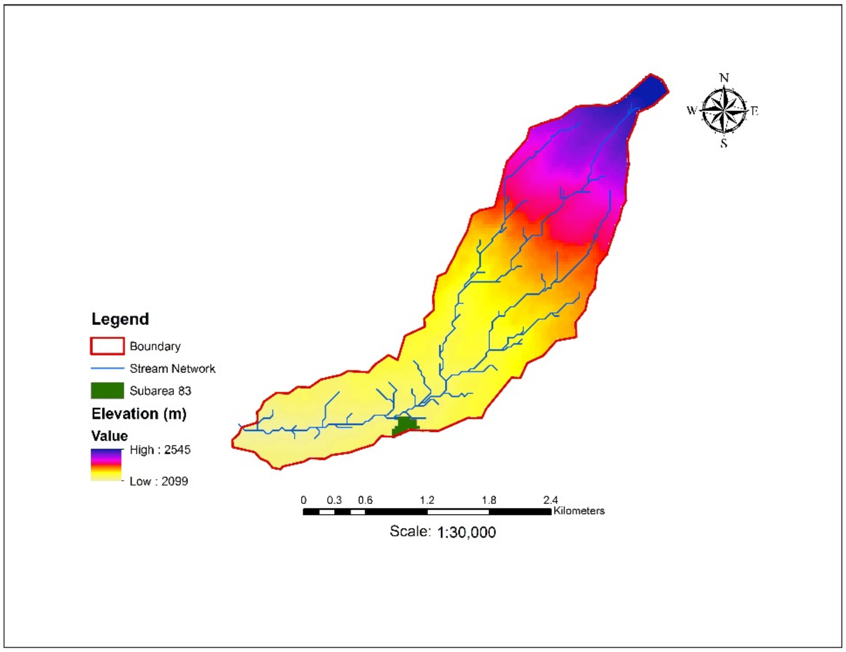

Figure 1. Lemo watershed boundary, main streams and Subarea 83, simulated with APEX.

Methods

Model Inputs. Input data used in this study for SWAT and APEX simulations included:

a) The 30-m resolution Digital Elevation Model (DEM) from SRTM Enhanced Shuttle Land Elevation Data (USGS EarthExplorer). These data were improved to 10-m resolution by re-projection with cubic convolution and using stream network burning to define streams, delineate the watershed, define slopes, and discretize subarea parameters. Five slope classes were defined within the watershed based on their varying suitability for irrigation (Chen et al. 2010; FAO 1997; Kassam et al. 2012; Mati et al. 2007). The slope classes were <2%, 2-8%, 8-12%, 12-20%, and >20%.

b) An existing land use map (MoWE 2012), used to improve the accuracy of predicted output from SWAT and APEX.

c) The soils map shape file (MoWE 2012), which classified the entire watershed area as Humic Nitisols (NTu). Soil parameters used by SWAT and APEX were estimated with the SWAT soil parameter generating tool.

d) Thirty-five years of daily weather data (1979-2013) were obtained from the National Centers for Environmental Prediction's Climate Forecast System Reanalysis (CFSR) climate data (Saha et al. 2010; Globalweather 2012). These data included rainfall, temperature (min/max), relative humidity, sunshine hours (solar radiation), and wind speed. Quality control of the data was performed to eliminate erroneous values that were beyond historical extreme records. Missing values were estimated using WXGN weather predictor. SWAT and APEX used the same weather dataset. Figure 2 illustrates monthly means and standard errors for the Lemo watershed.

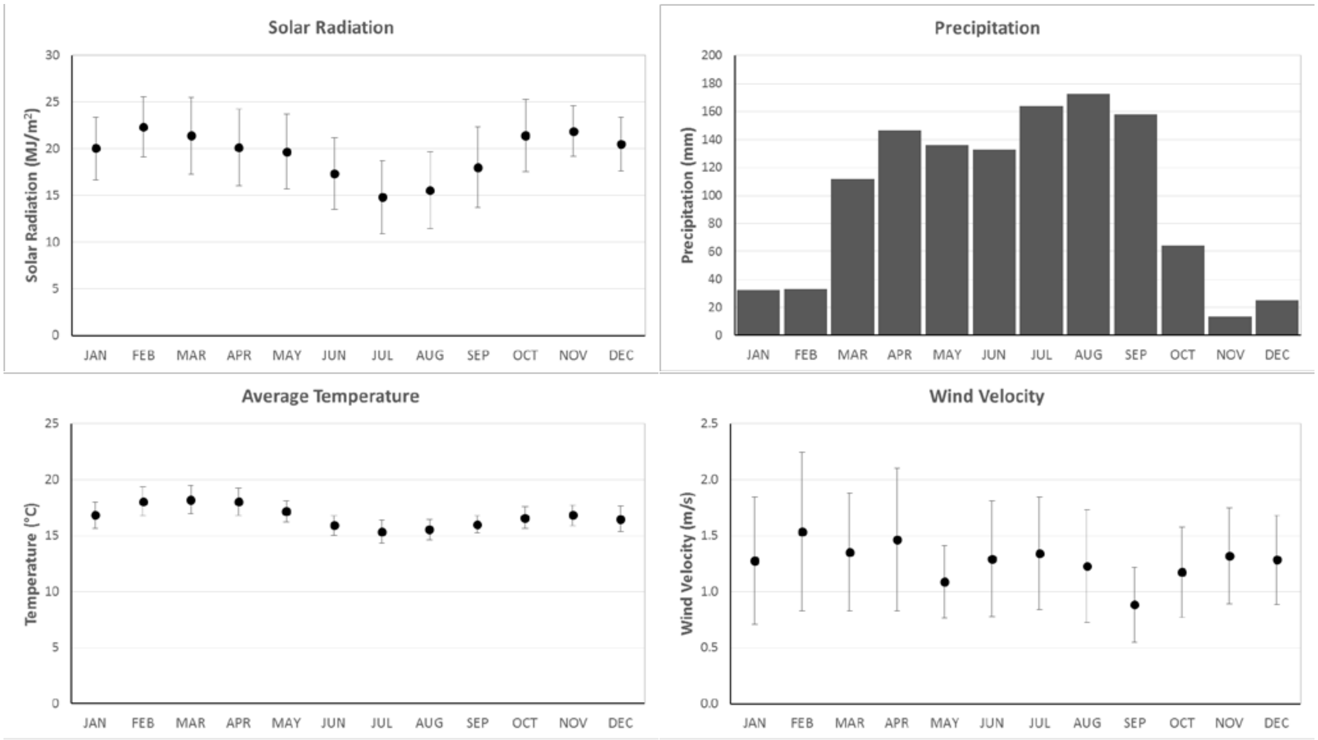

Figure 2. Monthly weather data for the Lemo watershed (1979-2013)

Subbasin Delineation. SWAT divided the 500-ha Lemo watershed into 98 subbasins (referred to as subareas in APEX) with areas ranging from one to ten hectares. The watershed discretization generated for SWAT was used to calibrate APEX to gauge streamflows and sediment yields. The subbasins/subareas were defined with assistance from International Water Management Institute staff. Subbasin/subarea shape and size were identical for the two models, to guarantee that SWAT and APEX streamflow volumes and sediment yields would be comparable.

As a case study, Subarea 83 (equivalent to SWAT's Subbasin 83) was selected for the simulation with APEX. Subarea 83 is 3.06 ha, characterized as cropland, and entirely composed of NTu clay soil, with a depth of 1.0 m, and a slope of 0.071 m/m. The latitude/longitude of its centroid was: 7.571 by 37.752

degrees, respectively. This area overlaps as well with the sample of households that were used for the farm-level economic and nutritional analysis (FARMSIM).

Crop Management. Generally, crop management in Ethiopia varies from farmer to farmer and from year to year, depending on when the rainy season begins. Table 1 provides baseline crop management data for maize, teff, and wheat, as simulated by SWAT and APEX. The baseline crop management schedules were based on farmer interviews and expert opinion. Baseline fertilizer application rates were based on IFPRI surveys.

Table 1. Crop management data used by SWAT and APEX for maize, teff and wheat in the Lemo watershed.

Date	Maize Practice	Amount
Aug-1	Tillage	
Aug-15	Tillage	
Aug-15	1st stage urea fertilizer application	26 kg/ha
Aug-15	DAP fertilizer application	52 kg/ha
Aug-15	Planting	
Sep-30	2nd stage urea fertilizer application	26 kg/ha
Dec-25	Harvest and kill	

Date	Teff Practice	Amount
Jun-30	Tillage	
Jul-22	Tillage	
Jul-22	1st stage urea fertilizer application	46 kg/ha
Jul-22	DAP fertilizer application	92 kg/ha
Jul-22	Planting	
Aug-22	2nd stage urea fertilizer application	46 kg/ha
Dec-5	Harvest	

Date	Wheat Practice	Amount
Jun-30	Tillage	
Jul-22	Tillage	
Jul-22	1st stage urea fertilizer application	42 kg/ha
Jul-22	DAP fertilizer application	84 kg/ha
Jul-22	Planting	
Aug-22	2nd stage urea fertilizer application	42 kg/ha
Dec-5	Harvest	

Onion is one of the region’s most common dry-season vegetable crops, and it is typically irrigated with shallow groundwater or river water. Fodder crops are also valuable in the woreda, and Lemo is one of the LIVES sites. Thus, for SWAT simulations, we considered onion and oats/vetch as dry season crops, with shallow groundwater as the source of irrigation. Irrigation was implemented in all areas designated for agricultural land use and with slopes of less than 8% (as recommended by FAO)—a total area of approximately 540 ha. Table 2 presents baseline crop management data for onion and oats/vetch used by SWAT. Crop management data for onion were based on Dile and Srinivasan (2014), while management data for oats/vetch were provided by the International Livestock Research Institute.

Table 2. Crop management for onion and oats/vetch in the Lemo watershed

Date	Onion Practice	Amount
Jan-1	Tillage	
Jan-5	Planting	
Jan-5	1st stage urea fertilizer application	85 kg/ha
Jan-5	DAP fertilizer application	35 kg/ha
Jan-5	Auto-irrigation begins	
Feb-20	2nd stage urea fertilizer application	85 kg/ha
Apr-11	Harvest and kill	

Date	Oats/Vetch Practice	Amount
Jan-1	Tillage	
Jan-5	Planting	
Jan-5	DAP fertilizer application	100 kg/ha
Jan-5	Auto-irrigation begins	
May-5	Harvest and kill	

Because this study proposed to evaluate fodder as a dry-season double crop—in contrast to local management practices, which dictate its cultivation during the region's rainy season— APEX assumed as a baseline the modified fodder management practices set forth in table 3.

Table 3. Modified baseline crop management practices for oats/vetch simulated by APEX

Date	Oats/Vetch Practice	Amount
October	Tillage	
Nov-1	Planting	
Nov-1	DAP fertilizer application	100 kg/ha
Nov-1	Auto-irrigation begins	
Feb-20	Harvest and kill	

The fertilizer rates in sub-Saharan Africa, and Ethiopia in particular, are generally low (IAASTD 2009). In Lower Gana kebele, fertilizer rates for teff and onion are low, though fertilizer rates for maize tend to approach recommended rates, set forth in table 4.

Table 4. Recommended fertilizer application rates in most parts of Ethiopia (EIAR 2007).

	*Urea (kg/ha)	DAP (kg/ha)
Teff	100	100
Maize	100	100
Wheat	100	100
Oats/Vetch	0	100
Onion	150	200

*The urea is applied in two split applications

Accordingly, SWAT and FARMSIM also simulated crop yield responses to application of fertilizer at recommended rates, as set forth in table 4. APEX simulated maize, teff and wheat yield responses to application of fertilizer at three different rates: (1) current fertilizer application rates; (2) at rates 20%

lower than current rates; and (3) at rates 20% higher than current rates. APEX also simulated fodder responses to application of fertilizer at two different rates: (1) baseline fertilizer application rates set forth in table 3; and (2) in addition to baseline, application of DAP at 100 kg/ha and urea at 100 kg/ha.

Stream Flow and Crop Yield Calibration. SWAT was calibrated to actual stream flow data gathered from a nearby river gauging station close to Hosaena town (MoWE 2012) and the calibrated parameters were transferred to the Lemo watershed (cf. Refsgaard 1997). APEX field-scale runoff values were calibrated to match SWAT predictions using the automatic calibration tool APEX CUTE.

Estimates of historical mean yields of maize, teff and wheat were obtained from the 2005 Spatial Production Allocation Model (SPAM) dataset (HarvestChoice 2014) for an area including Upper Gana. In SPAM, teff is included in the “other cereals” category, but it is by far the most important representative of that group in the area. (HarvestChoice 2014). Therefore, SPAM yield estimates for “other cereals” were used to calibrate yields of teff. Table 5 gives SPAM grain yields (t/ha, dry weight) for maize, teff and wheat for the 2005 cycle (HarvestChoice 2014). Statistical analyses could not be performed for calibration of yields since the number of samples used for calibration of each crop was limited. Onion yield estimates used in model calibration were acquired from the Ethiopian Central Statistical Agency (2012).

Table 5. SPAM estimates of maize, teff and wheat yields for three grid cells associated with the Lemo watershed.

Region	Cell ID	Maize	Teff	Wheat
Lemo	4270773	1.44 t/ha	0.80 t/ha	1.40 t/ha
Lemo	4275093	1.66 t/ha	0.80 t/ha	1.11 t/ha
Lemo	4275092	1.70 t/ha	0.80 t/ha	1.05 t/ha

Economic Analyses. FARMSIM was used to provide economic analyses of several promising SSI interventions identified by SWAT and APEX simulations. These included: (1) increased cultivation of irrigated, dry-season, double crops of onions and fodder; and (2) the evaluation of five alternate water-lifting technologies. In all cases, FARMSIM simulated fertilization of teff, maize, wheat, fodder and onion crops at rates recommended by the Ethiopian government.

The baseline and five alternative scenarios were each defined as follows:

Baseline: no irrigation + current fertilizer

Alt.1: pulley-and-bucket pump irrigation + recommended fertilizers

Alt.2: hand-operated rope-and-washer pump irrigation + recommended fertilizers

Alt.3: animal-powered rope-and-washer pump irrigation + recommended fertilizers

Alt.4: gasoline motor-powered rope-and-washer pump irrigation + recommended fertilizers

Alt.5: solar-powered pump rope-and-washer irrigation + recommended fertilizers

Though not widely used in Ethiopia, rope-and-washer pumps powered by animals, gasoline motors and solar power are utilized in other parts of Africa, as pictured below, and may be viable options for SSI:

Pulley-and-bucket system

Hand-operated rope-and-washer pump

Rope-and-washer pump operated by horse

Gasoline-motor-powered rope-and-washer pump

Solar-powered rope-and-washer pump

For the sake of brevity, we will hereinafter refer to hand-operated rope-and-washer pumps, animal-powered rope-and-washer pumps, gasoline motor-powered rope-and-washer pumps, and solar-powered rope-and-washer pumps as “hand-operated pumps”, “animal-powered pumps”, “motor pumps” and “solar pumps”, respectively.

In comparing the five irrigation technologies, we estimated the costs of employing each technology, as well as the amount of land that could be irrigated by each without water stress to the crops. Estimates were based on the costs (operating and capital) of each technology and the capacity of each (as determined by its pumping rate) to irrigate available land. Our analysis assumed the following:

1) Number of active family members (adults) required to carry out the irrigation: 2
2) Number of irrigation hours per family member per irrigation day: 4
3) Number of irrigation days per season, assuming irrigation every other day during a period of 3.5 months (January through mid-April): 55
4) Total number of hours of irrigation per season: 2*4*55 = 440 hours
5) Pumping rates for the different water-lifting technologies:
    - Pulley and bucket: 8 L/min
    - Hand-operated pump[1]: 20 L/min
    - Animal-powered pump[2]: 60 L/min
    - Motor pump[3]: 170 L/min
    - Solar pump[4]: 24 L/min

Crop yields were simulated by APEX for different levels of water stress. The irrigator’s equation was used to estimate the total amount of water that can be delivered by a water lifting technology:

Irrigator’s equation: $Q*t = d*A$

Q: flow or pumping rate (L/min)
T: time for irrigation (min)
d: depth of irrigation water applied (mm)
A: area covered (m^2 or ha)

Based on the total amount of water required to irrigate a crop for the entire dry season, and the total amount of water per hectare delivered by each water-lifting technology (based on pumping rate and irrigation hours), we computed the fraction of water supply provided by each technology. For this particular case (with two irrigated crops), we chose onion as the reference crop to compute the fraction covered since it requires more irrigation water than fodder. Given the total irrigable land available for an irrigated onion crop and its water requirements, we used the amount of water that could be supplied by each technology to compute the fraction of cropland that could be irrigated with minimal water stress for each water-lifting technology.

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[1] Nederstigt and Van del Wal 2011/PRACTICA Foundation
[2] http://www.ropepumps.org/horse.html/PRACTICA Foundation
[3] IWMI field studies conducted in 2015 on behalf of ILSSI project
[4] Mzuzu University in Malawi: http://old.solar-aid.org/project_water_pump/

The irrigation water requirements at the Lemo site (where both onions and vetch were irrigated—as opposed to only onions at the other three ILSSI sites) were three times higher than the irrigation water requirements at the Robit and Adami Tulu sites, and more than 15% higher than the irrigation water requirements at Dangila. Even though irrigation time was doubled for the Lemo site (with irrigation every other day as opposed to two times a week for the other ILSSI sites), none of the water-lifting technologies was able to provide the required irrigation water to grow onion and fodder without water stress on all 540 ha of total irrigable land in the kebele. The pulley irrigation system covered only 5% of total irrigable land, the hand-operated pump covered 12%, the solar pump covered 14%, and the motor pump and animal-powered pump covered 70% and 35%, respectively.

Other simulation assumptions

First, to show the full potential of adopting new technologies, we assumed that the alternative farming technologies (alternative scenarios) simulated in this study were adopted at 100% by farmers. Second, the markets were assumed to be accessible and to function at a competitive level with no distortion where the supply and demand determine the market prices. However, in the five-year economic forecast, market selling price in each of the five years was assumed to equal the average selling price of year 1 for each crop sold.

The FARMSIM model was run 500 times for each of the six scenarios—the baseline scenario and five alternate scenarios—to sample variation in crop yields due to weather and other stochastic variables. To determine which of the six scenarios would be most beneficial to farm families, three types of economic indicators were calculated: Net Present Value (NPV), Net Cash Farm Income (NCFI), and Ending Cash (EC) reserves. The performance of the six scenarios as estimated by each of the three indicators was displayed graphically as a cumulative distribution function (CDF) and as a “stoplight graph.”

Results and Discussion.

Hydrology. Our results indicated that there is great potential for additional small-scale irrigation in the Lemo watershed. The average annual groundwater recharge simulated by SWAT was 287-316 mm (fig. 3), and the annual generated surface runoff was estimated to be 186-194 mm. For the Lemo watershed, with a catchment area of 500 ha, the average annual volumetric groundwater recharge and surface runoff potentials are over 1.5 million m^3 and 0.96 million m^3, respectively. Small-scale irrigation interventions can be utilized to make use of these natural resources efficiently.

b)

Figure 3. Water resources potential in the Lemo watershed; a) the average annual groundwater recharge, and b) surface runoff.

For SWAT simulations, irrigation water was derived from shallow groundwater. Therefore, it was necessary to determine whether shallow groundwater recharge could support irrigation water requirements when irrigated, dry-season onions and fodder were cultivated. The average annual shallow groundwater recharge under baseline conditions was more than 272 mm across the 500-ha watershed. The average annual area-weighted irrigation in the subbasins varied from 0-83 mm (fig. 4). Mean annual irrigation was less than 10% of mean recharge in the entire watershed. Therefore, we can safely conclude that irrigation of onion and fodder during the dry season can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage.

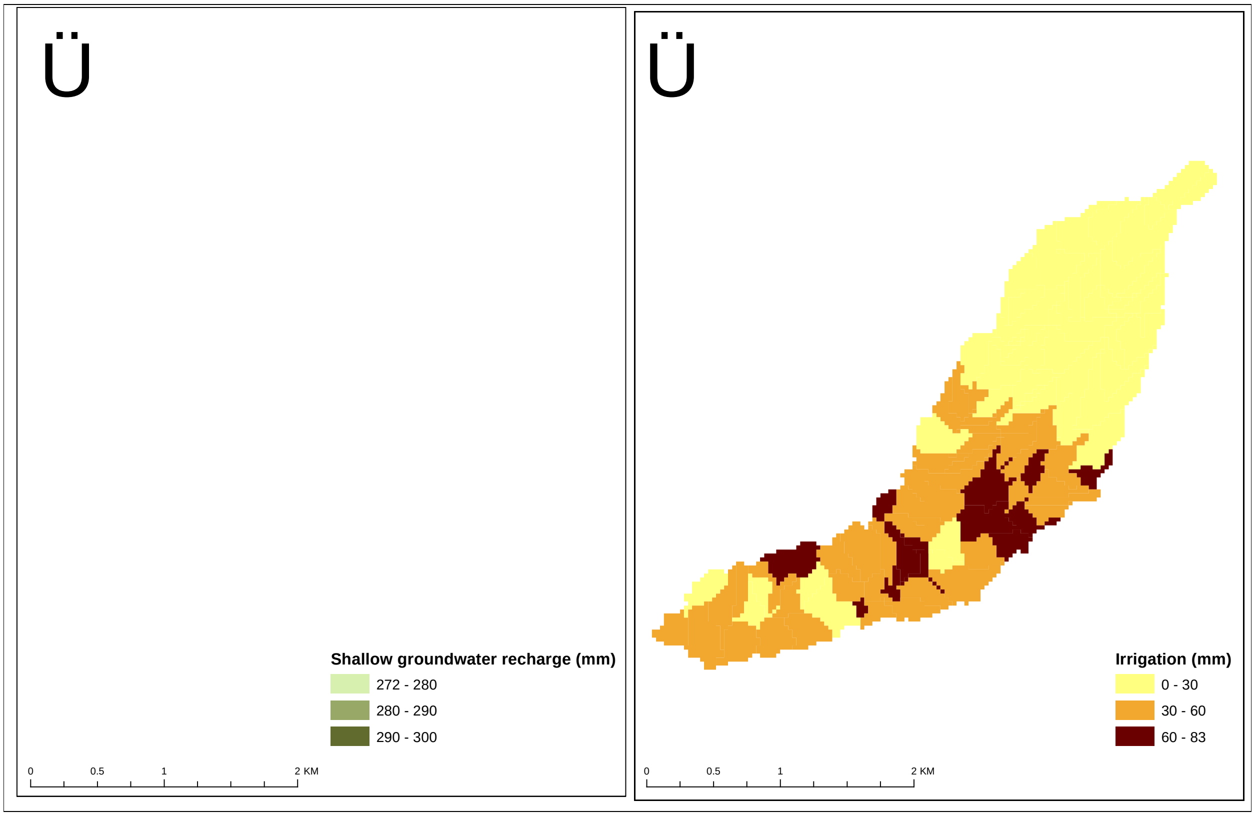


Figure 4. a) Average annual shallow groundwater recharge under baseline conditions, and b) average annual irrigation for cultivating onion and fodder during the dry season.

Annual water balance components for maize, teff and wheat as estimated by APEX are illustrated in figure 5.

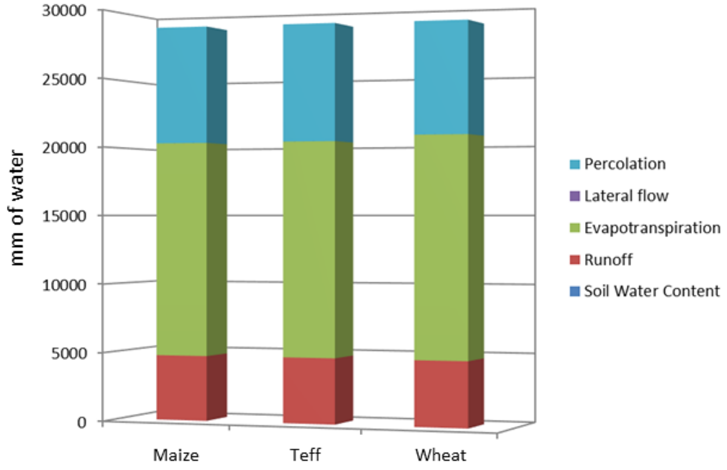


Figure 5. Water balance for maize, teff and wheat in Lemo watershed estimated by APEX.

The average annual rainfall in the Lemo watershed for the period 1990 to 2013 was 1193 mm. About 34% of the annual rainfall became stream flow and 57% was evaporated back into the atmosphere (fig. 6). Surface runoff contributed 48% of stream flow and base flow contributed 52%.

Figure 6 illustrates the simulated hydrology of the Lemo watershed for the baseline cropping system without irrigated onion and fodder, as compared to the same cropping system with irrigated onion and fodder. Dry season onion and fodder irrigation on all land with less than 8% slope slightly reduced stream flow from 34% to 32% of precipitation because the pumping of groundwater from the aquifer reduced base flow. However, it also caused a small increase in the fraction of stream flow derived from surface runoff, probably because increased in soil moisture affects surface runoff generation. Actual evaporation increased to 60% of rainfall when irrigated, dry-season onions and fodder were cultivated, but the ratios of percolation to rainfall and deep recharge to rainfall did not change.

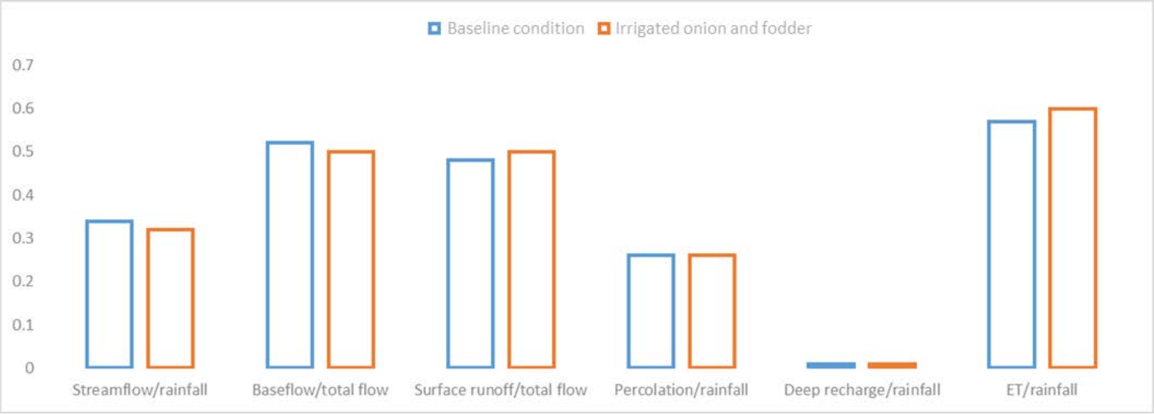


Figure 6. Water balance partitioning for the Lemo watershed for the baseline cropping system and for the same cropping system with irrigated onion and fodder.

Irrigation of dry-season onion and fodder caused a slight reduction in average stream flows simulated by SWAT at the outlet of the Lemo watershed. The average monthly stream flow for the non-irrigated baseline scenario from 1995 to 2013 was 0.066 m^3/sec. Addition of irrigated onion and fodder to the cropping system during this same time period reduced the average monthly stream flow by 5.6% to 0.062 m^3/sec, and also produced minor reductions in peak flows (fig. 7). The increase in fertilization from baseline to recommended rates resulted in only minor reductions in average monthly stream flow. These results suggest that implementation of SSI on 540 ha of the 1630-ha Upper Gana kebele (all cropland with less than 8% slope) to produce high-value, dry-season crops should not compromise downstream flows.

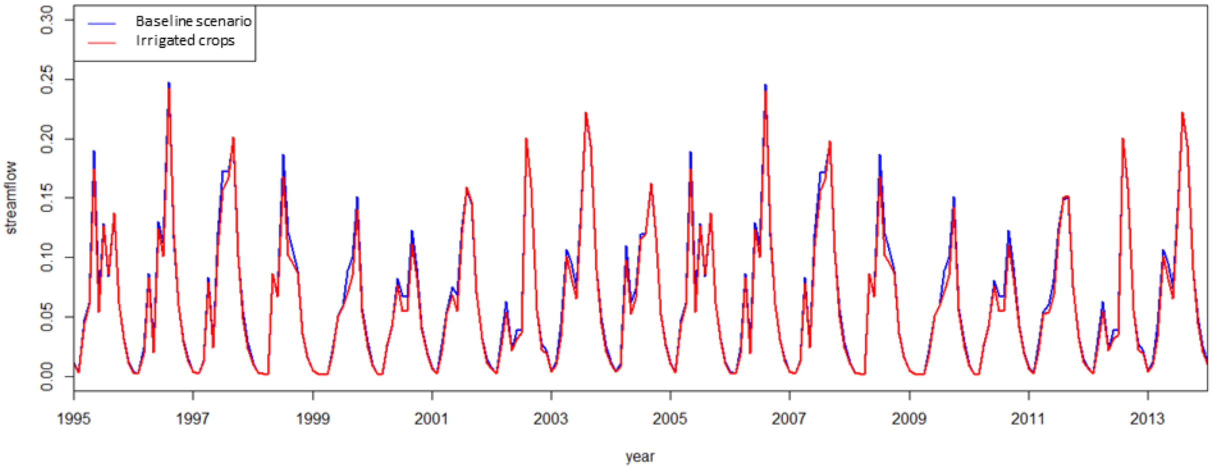


Figure 7. Stream flow at the outlet of the Lemo watershed for the baseline cropping system and for the same cropping system with irrigated onion and fodder.

Crop yields. Calibrated APEX cereal yields were similar to those estimated by SPAM (fig. 8). Once APEX crops were calibrated, the crop parameters were transferred to SWAT. Calibrated crop yields for 24-year weather were transferred to FARMSIM for socio-economic analyses.

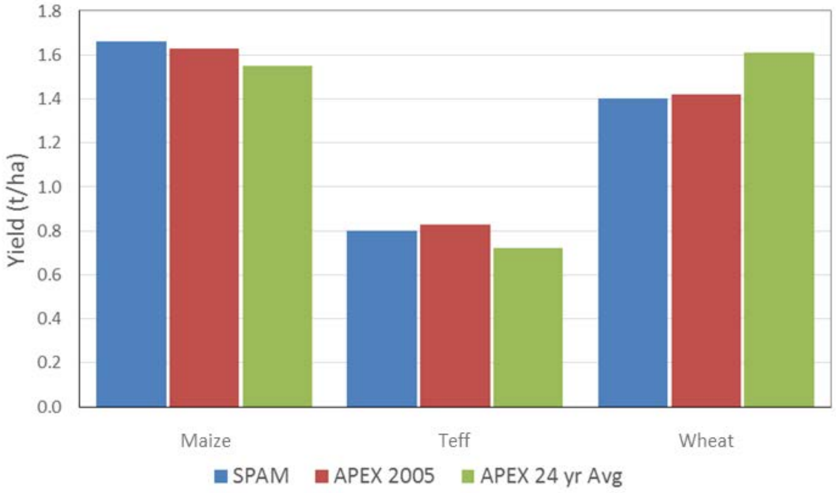
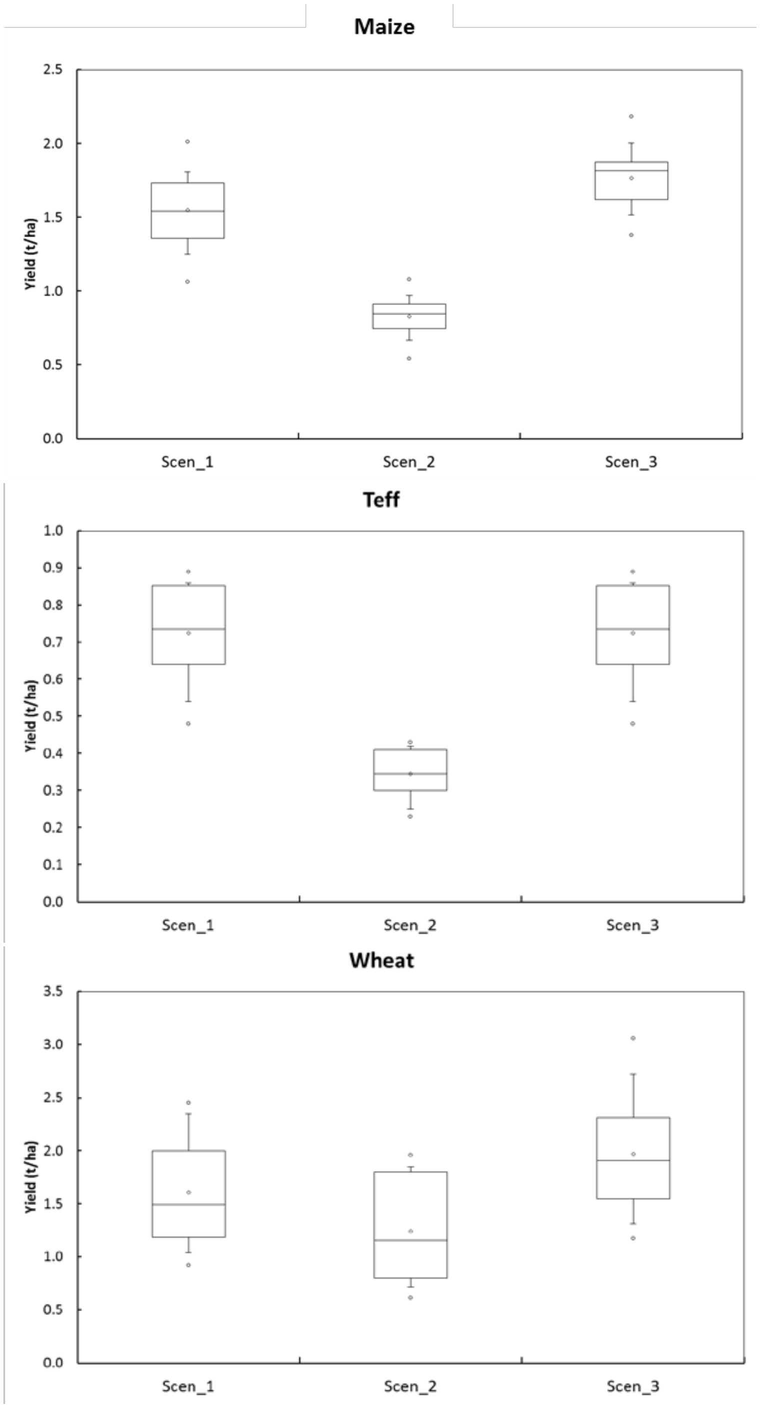


Figure 8. Comparison of maize, teff, and wheat yields from SPAM 2005 with APEX-simulated yields in 2005 and APEX-simulated yields averaged over the 24-year period (t/ha dry weight).

APEX-simulated crop yields of maize, teff and wheat are depicted in figure 9. Results indicate that increasing the current fertilizer application rate by 20% will increase yields of maize and wheat by 14% and 22%, respectively, while having very little impact on teff yields. In contrast, reducing current fertilizer application rates by 20% reduces maize and teff yields by 50% and wheat yields by 22%.


Maize

Teff

Wheat

Figure 9. APEX-simulated crop yields for maize, teff and wheat under: (1) Scenario 1: current fertilization rates; (2) Scenario 2: 20% reduction in current fertilization rates; and (3) Scenario 3: 20% increase in current fertilization rates

APEX-simulated fodder yields are depicted in figure 10. Results indicated that, as compared to the current practice of applying DAP at a rate of 100 kg/ha (Scenario 1), applying urea in addition to DAP, both at rates of 100 kg/ha (Scenario 2) increased fodder yields of the 24-year period by 123%.

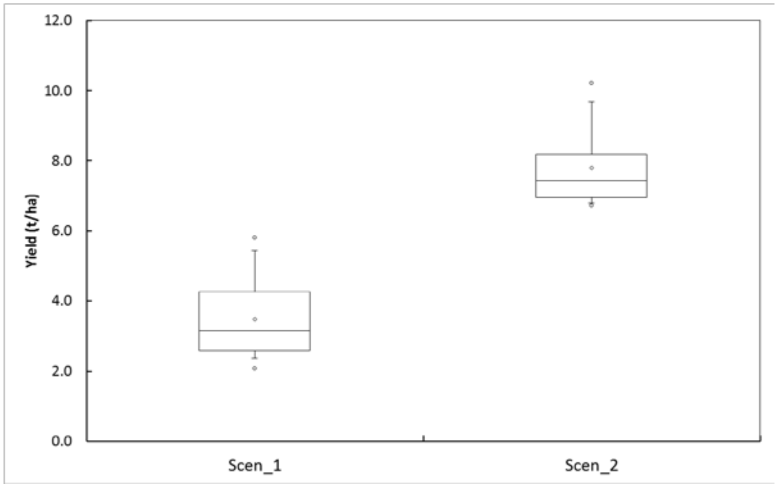
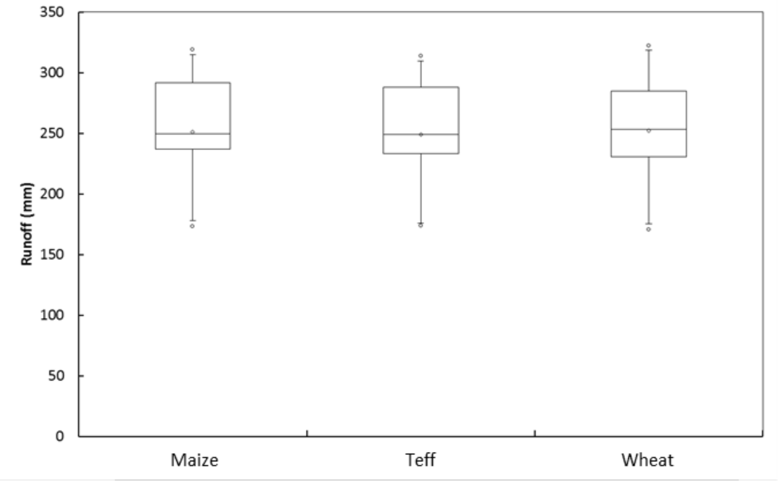


Figure 10. APEX-simulated crop yields for fodder under: (1) Scenario 1: current fertilization rates; (2) Scenario 2: current fertilization rates plus 100 kg/ha of urea

Runoff and Soil Erosion. Simulated field-scale runoff and edge-of-field sediment yield were simulated with APEX. There was not a statistical difference between the rain-fed monocrops with respect to runoff (fig. 11). There was, however, a statistically significant difference with respect to sediment loss (fig. 11). For the study period, maize reduced sediment loss by 12% and 6%, respectively, compared to teff and wheat.



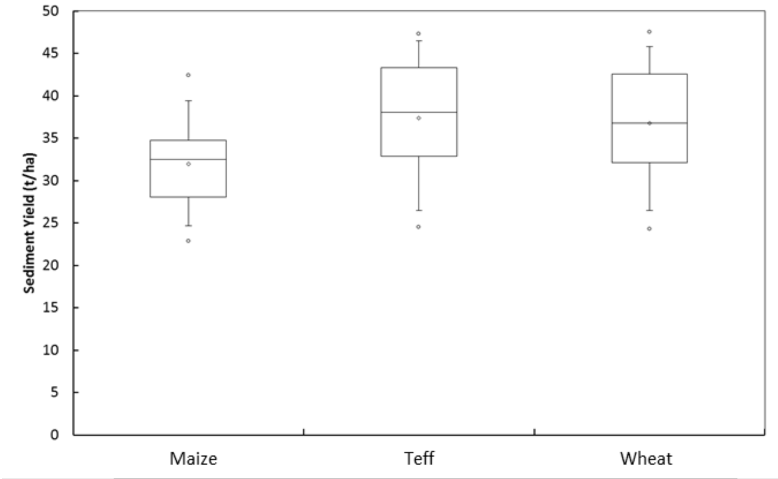


Figure 11. Runoff and sediment yield for rain-fed monocrops.

With respect to fodder, runoff and sediment yield were similar for both fertilization scenarios (fig. 12):

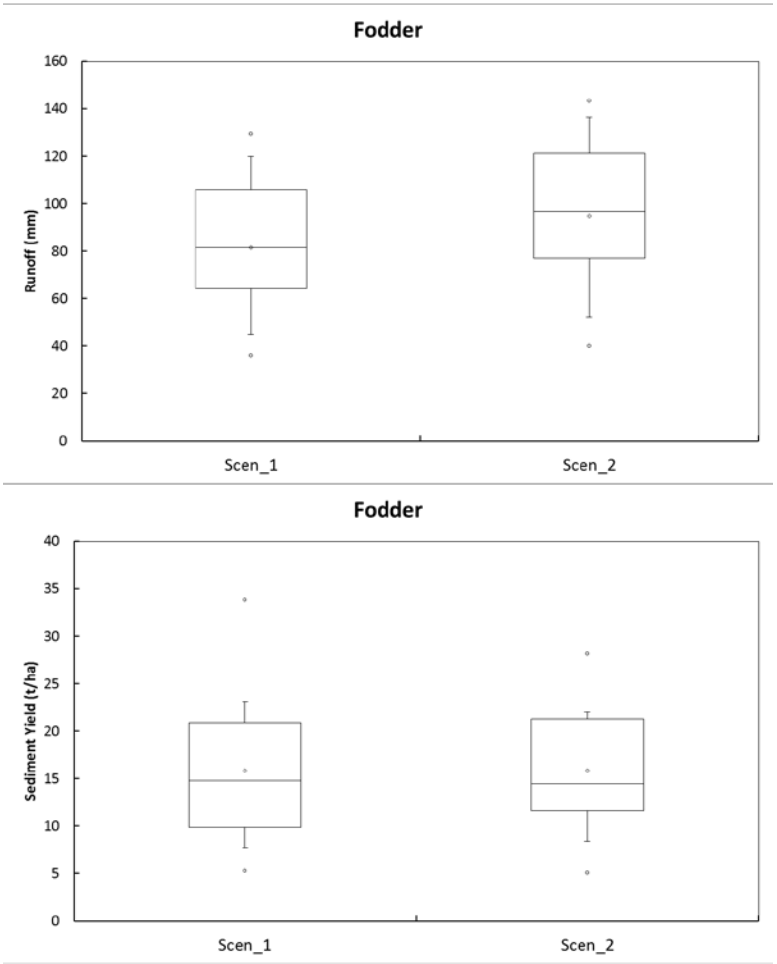


Figure 12. APEX-simulated crop yields for fodder under: (1) Scenario 1: current fertilization rates; (2) Scenario 2: current fertilization rates plus 100 kg/ha of urea

Irrigation effects. There is often a strong relationship between the amount of irrigation water supplied to a crop and that crop's yields. However, the relationship is sensitive to crop, land, soil, weather, and management practices (Vaux and Pruitt 1983; de Juan et al. 1996; Brumbelow and Georakakos 2007). Because APEX and SWAT simulate the interacting effects of soil, land, weather and management on the crop, they can be used to simulate complex combinations of natural resource and management variables.

We simulated the production of irrigated onions with the automatic irrigation feature of APEX. We set model parameters to simulate irrigation at several plant stress levels, ranging from near zero (non-stressed) to 85% (highly stressed). Equation 1 and figure 13 describe the simulated relationship between onion yield and the quantity of irrigation water applied.

$$Y = -0.000007x^2 + 0.008x + 0.795 \ (R^2 = 0.98) \qquad \text{[Eq. 1]}$$

Where: Y is crop yield (t/ha) and x is irrigation water applied (mm)

As expected, onion yields increase with applied water up to 455 mm:

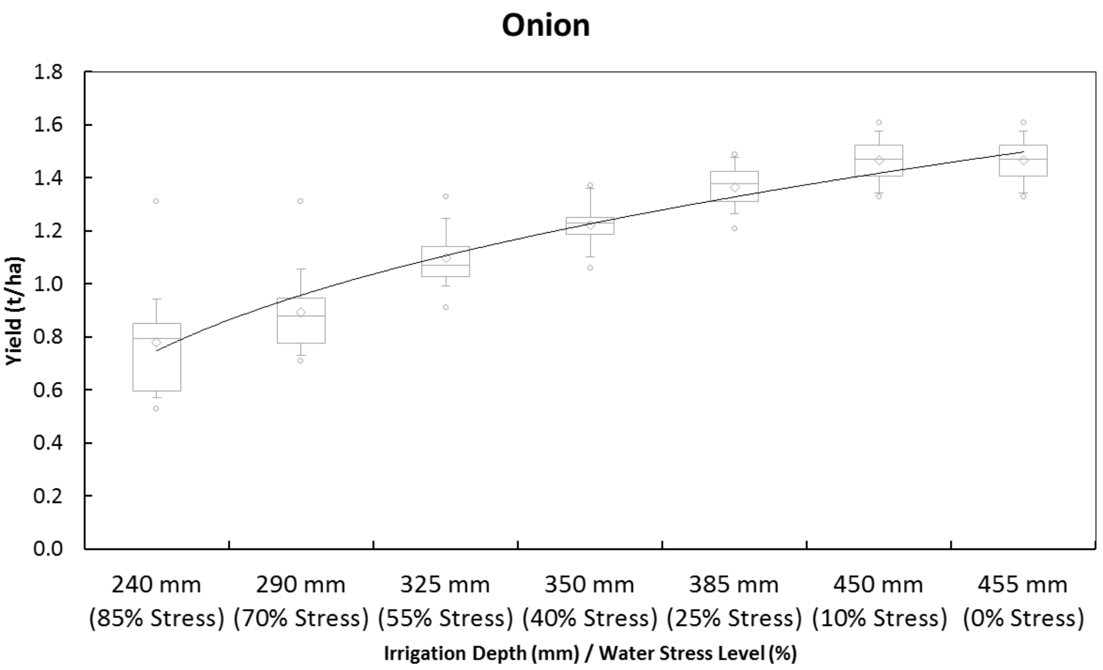


Figure 13. Onion yield (t/ha oven-dry weight) in Lemo watershed as a function of irrigation water applied.

Water supply for irrigation from hand-dug, shallow wells is contingent on well depth, each well's recharge rate, and the capacity of pumps to lift water. The depth and recharge rates of shallow wells are quite variable and they are dependent on the soil and the geologic and surface characteristics of each location.

For the following analysis, we assumed that shallow ground water was 10 m below the surface, and the aquifer was adequate to supply the irrigation water required by the crop. Therefore, irrigation water supply was limited by the capacity of the pumping technology. In Ethiopia, human power, animal traction, and motor pumps are used to pump irrigation water. Using the irrigations requirements for onion estimated with APEX (Eq. 1) and pumping rates for a pulley and bucket (0.25 l/s), a hand-powered pump (0.6 l/s) and a motor pump (1.36 kW; 14.0 l/s) (pumping rates taken from Awulachew et. al 2009; Brikke, F. and M. Bredero 2003), we estimated the times required to irrigate 0.25 ha with each method. For example, to achieve a mean onion yield of approximately 13.6 t/ha (fresh weight) on 0.25 ha required application of about 60 mm of irrigation water. To deliver this quantity of water to the crop over the growing season required 66.4 hours with a pulley and bucket, 27.7 hours with a hand-powered pump, and 1.2 hours with a motor pump.

Economic Analyses. NPV is an indicator that assesses the feasibility and profitability of an investment or project over a certain period of time. Comparison of the CDFs of the six scenarios indicated that it is worth investing in certain methods of irrigation and recommended fertilizer application (fig. 14a). The use of recommended fertilizers on grain crops, in combination with onion and fodder crops irrigated with animal-powered and motor pumps (Alts. 3 and 4) were by far the most economically profitable alternatives (their CDF values lie far to the right of the other scenarios for all 500 draws of the simulation model). The next-best-performing scenarios involved the application of recommended fertilizers and hand-powered or solar pump irrigation (Alts. 2 and 5),. Irrigation by pulley and bucket (Alt. 1) was the lowest performing scenario, with lower NPV values than the baseline, non-irrigated scenario.

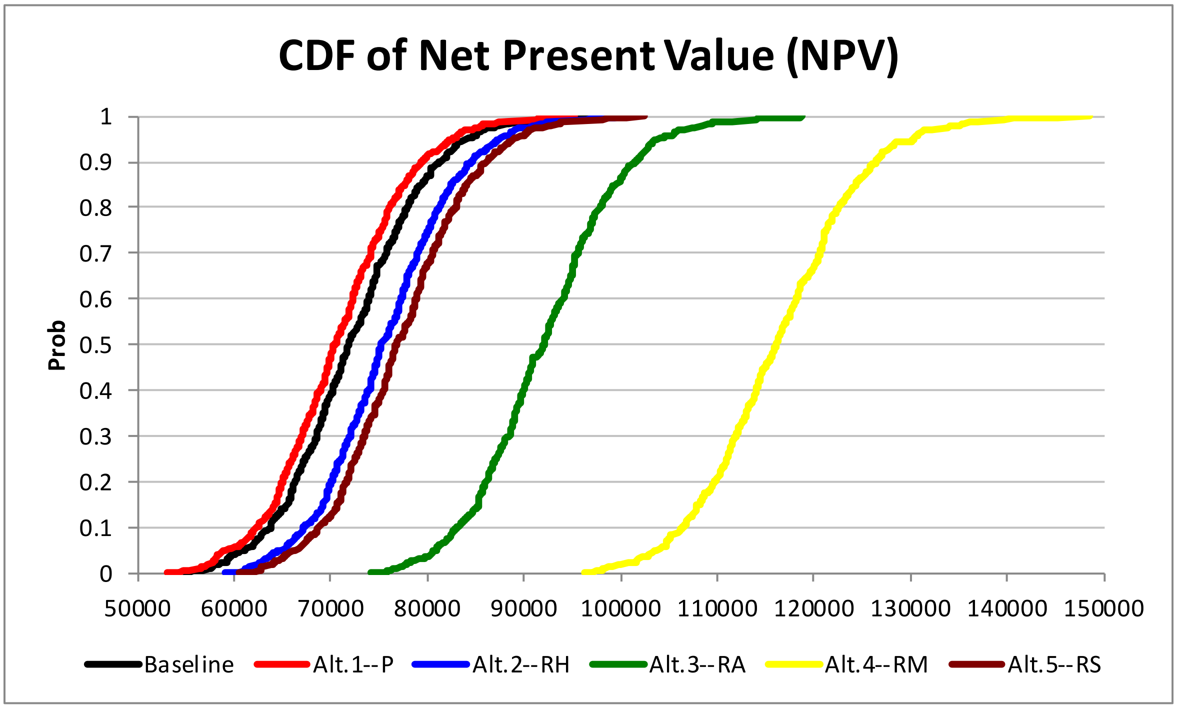


Figure 14a. Net present value for the six scenarios

The stoplight chart presents the year-three probabilities of NPVs of less than 70,000 Ethiopian Birr (ETB) (red), greater than 105,000 ETB (green), and between the two target values (yellow) for the six scenarios. The target values are the averages of NPV for the baseline scenario (lower bound) and the best-performing alternatives (Alts. 3 and 4) (upper bound). For a farmer in the baseline scenario, there was a 39% chance that NPV would be less than 70,000 ETB, and a 0% chance that NPV would exceed 105,000 ETB (fig. 14b). For farmers using a motor pump (Alt. 4), the probability that NPV would exceed 105,000 ETB was 92%, compared to only 4% for farmers using animal-powered pumps. The main barrier for the best-performing scenario (Alt. 4) was the initial investment in the water-lifting technology. The cost of a motor or solar pump is about two times greater than the cost of an animal-poweredpump; however, the NPV results strongly suggest that the investment in motor and animal-powered pumps would pay large dividends in increased income and wealth.

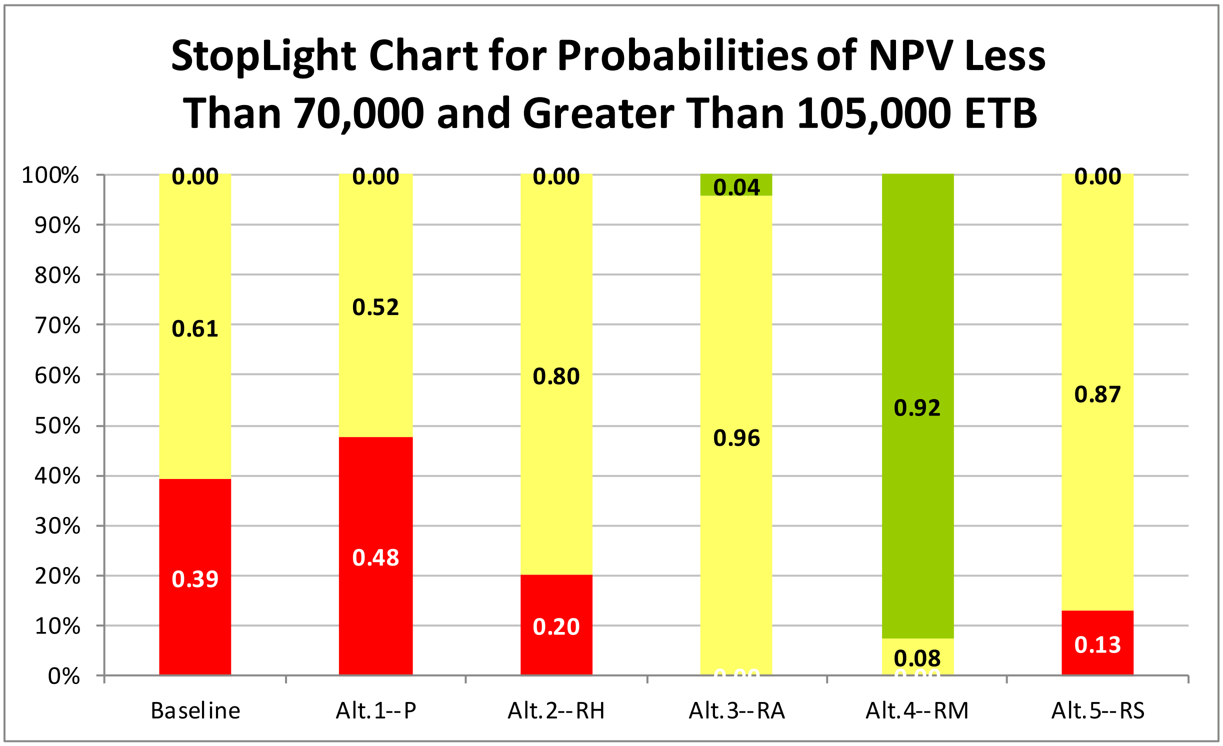


Figure 14b. Stoplight chart for the NPV for the six scenarios

The annual net cash farm income (NCFI) simulation results represent the profit for a farmer in year three of the five-year planning horizon. The CDF graph for NCFI shows a clear difference between the two best-performing scenarios—animal-powered- and motor-pump irrigation (Alts. 3 and 4)—and the rest of the scenarios (fig. 15a). Alternatives 3 and 4 generated higher levels of NCFI at all probability levels, making them the preferred scenarios for decision makers. The difference between NCFIs in Alternatives 3 and 4 and those in the remaining scenarios is due to increased irrigation coverage provided by animal-powered and motor technologies, and the resulting increases in surplus onion and fodder available for sale in these scenarios. Note that the baseline scenario (without irrigation) performed slightly better than pulley-and-bucket irrigation (Alt. 1), suggesting that investing in the pulley-and-bucket system to cover more irrigable land would cost more than growing non-irrigated onions and fodder.

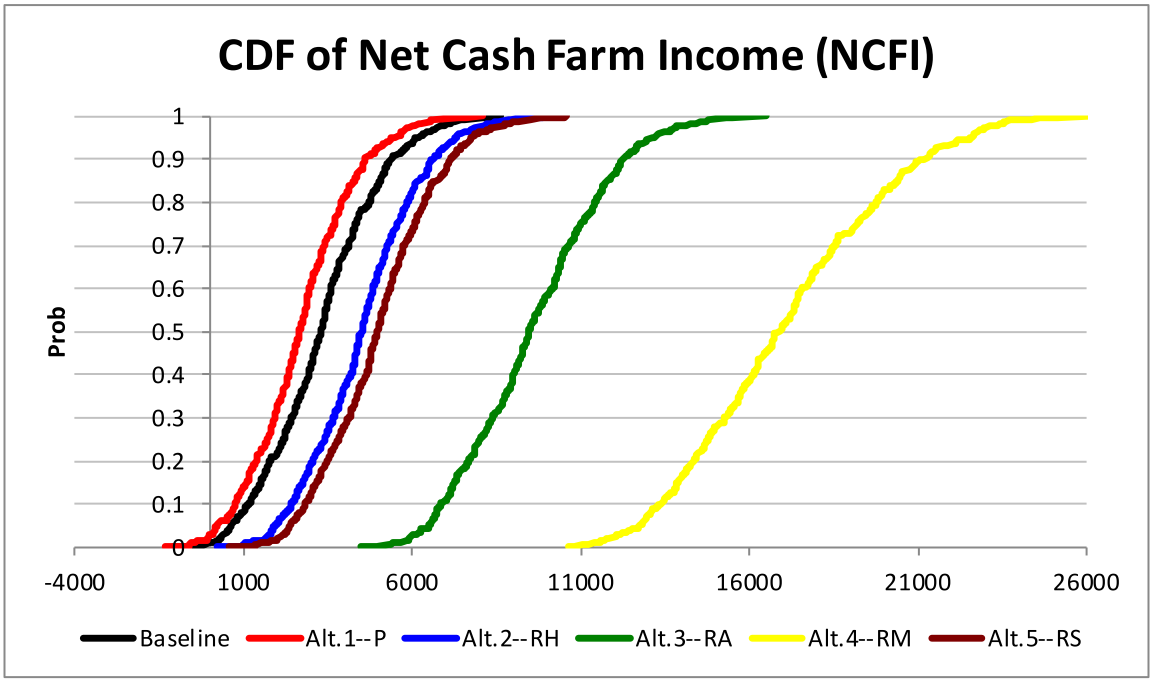


Figure 15a. Net cash farm income for the six scenarios

The stoplight chart for NCFI in year three of the planning horizon shows that, in the baseline scenario, there was a 42% probability that a farm would generate NCFI of less than 3,000 ETB, and a 0% chance that NCFI would exceed 13,000 ETB (fig. 15b). A farm that irrigated with a pulley and bucket (Alt. 1) was even more likely to generate NCFI of less than 3,000 ETB (61%) than a farm that did not irrigate, because of the costs involved in using the irrigation system. For a farm that adopted hand-operated or solar pump irrigation (Alts. 2 and 5), the likelihood of generating NCFI of less than 3,000 ETB was only 20% and 13%, respectively, but in both cases there was a 0% chance of generating revenues of more than 13,000 ETB. In contrast, for a farm that adopted animal-powered or motor pump irrigation (Alts. 3 and 4), there was a 0% chance that NCFI would be less than 3,000 ETB, and a 5% or 92% chance, respectively, that NCFI would exceed 13,000 ETB.

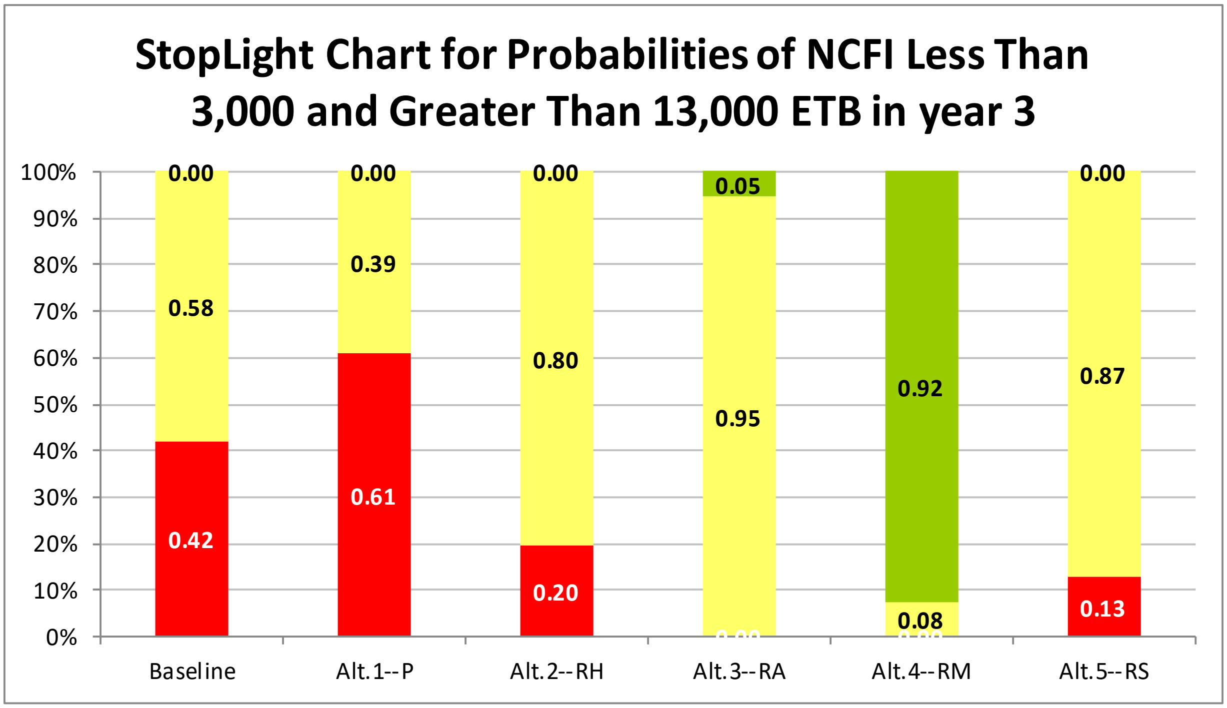


Figure 15b. Stoplight chart for NCFI.

The Ending Cash (EC) reserve indicator (fig. 16a) highlighted once again the superior performance of animal-powered and pump irrigation (Alts. 3 and 4). The CDF values for alternatives 3 and 4 lie entirely to the right of the baseline and all other scenarios, indicating that a farmer who invested in these technologies was far more likely to have higher EC reserves at the end of the five-year planning horizon. Note that, again, a farmer who did not irrigate (baseline) performed as better than one who adopted pulley-and-bucket irrigation (Alt. 1).

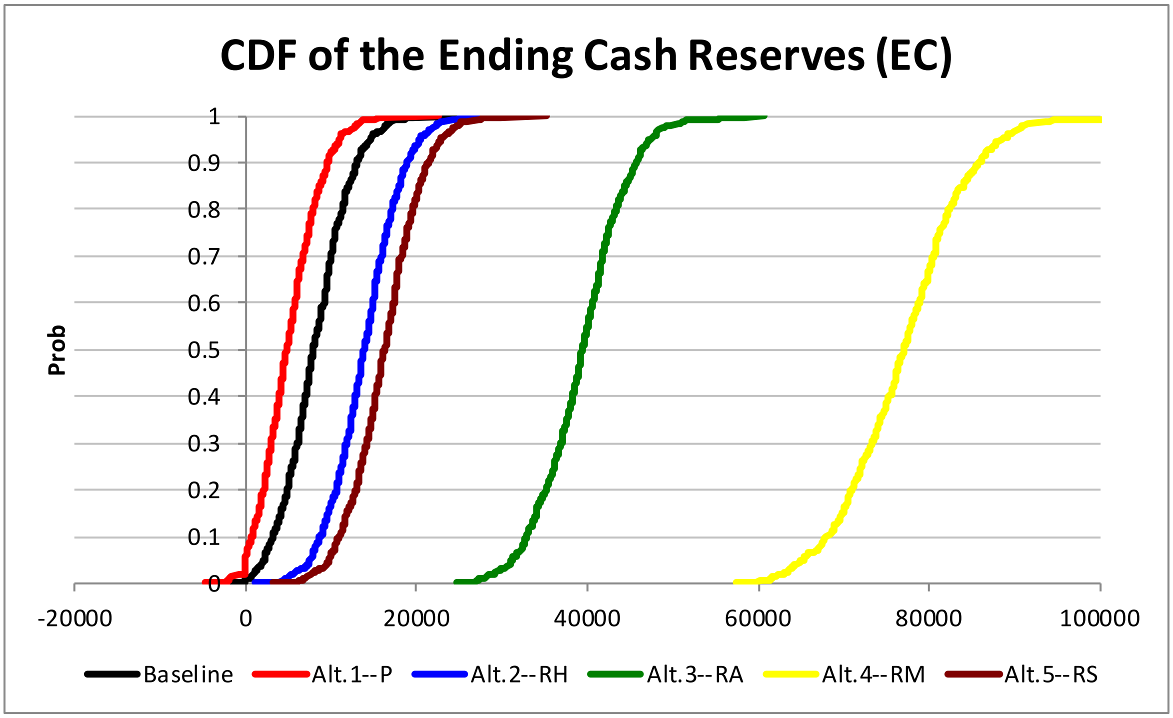


Figure 16a. Ending cash reserve (EC) for six scenarios

The stoplight chart for EC reserves (fig. 16b) shows that, in year five, a farmer who did not irrigate (baseline) had a 22% probability of having EC reserves of less than 5,000 ETB (baseline average) and a 0% probability of having EC reserves of more than 77,000 ETB. In contrast, a farmer who irrigated with a motor pump (Alt. 5) had a 51% probability of having EC reserves of more than 77,000 ETB in year 5 and a 0% probability of EC reserves under 5,000 ETB. The motor-pump scenario far outperformed the three next-best scenarios, since a farmer who irrigated with a hand-operated, animal-powered, or solar pump had a 99% -100% chance of generating EC reserves between 5,000 ETB and 77,000 ETB. Again, a farmer who irrigated with a pulley and bucket (Alt. 1) was more likely to generate EC reserves under 5,000 ETB than one who did not irrigate at all.

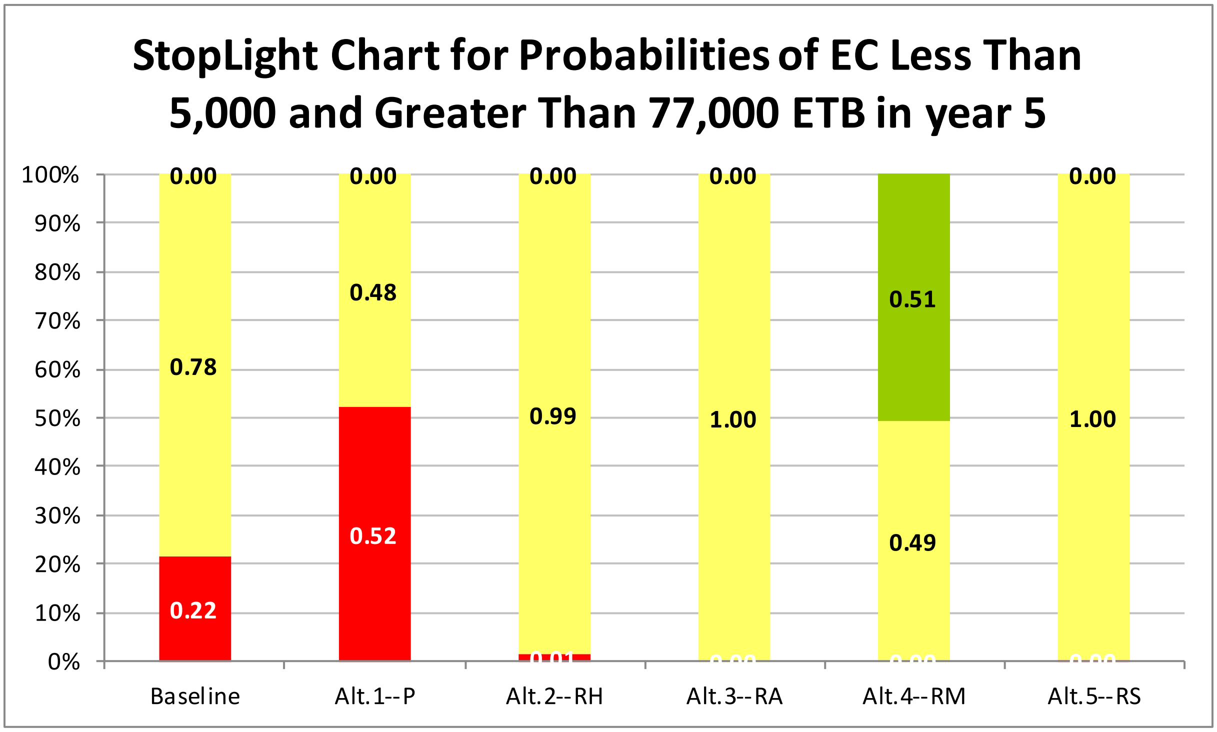


Figure 16b. Stoplight chart for the ending cash reserves (EC)

Since grain crops in the region are used mainly for family consumption, the increases in farm revenue in each of the alternative scenarios were due primarily to the sale of surplus irrigated fodder and onion. For example, where a farm implemented motor-pump irrigation (Alt. 4), the forecasted sales of fodder and onion would contribute on average 62% and 17%, respectively, of total crops receipts, and 83% and 17%, respectively, of net cash (profit) for the five-year planning horizon.

The outcomes of the various irrigation technologies in the three indicators discussed above varied widely. This variation highlights the high irrigation water needs and risk for onion and fodder production in Upper Gana kebele. Moreover, the motor pump seems to be the only promising irrigation technology in this study to reduce income risk and generate profit.

Nutrition. In general, adoption and proper use of agricultural technologies lead to an increase in the quantity and variety of crops produced. The implications for nutrition vary according to the types of crops grown and consumed; in most cases, surplus food can be sold at market and resulting revenues can be used to buy supplemental food items as needed to meet nutrition requirements. This study did not evaluate the impact of fodder production on a farm family's livestock production (e.g., whether increased fodder production could lead to increases in the numbers of animals raised, consumed, and sold), but assumed all fodder (as well as onion) would be treated as surplus and produced strictly for sale. Similarly, the study did not evaluate how additional revenues from the sale of onion and fodder might be spent to meet nutritional needs, but simply predicted the additional revenue generated by sales of each. Farm-family nutrition could improve if the earnings from onion and fodder production were used to purchase other food products.

Simulations indicated that in most cases the nutrients available to farm families decreased under the irrigated scenarios, possibly because some of the land was reallocated to fodder production. In all of the alternative scenarios, the minimum requirements per adult equivalent per day were met for calories, protein, and iron; however, nutritional deficiencies in fat, calcium, and vitamin A persisted. Clearly, families in Lemo require food supplements (whether obtained by farming and consuming additional irrigated vegetable crops that meet nutritional needs, or by using revenues from irrigated crops to purchase additional vegetables and other supplements) to meet minimum nutritional requirements for fat, calcium, and vitamin A. The analysis and comparison of alternative irrigated crops and their effects on farm-family nutrition are subjects for proposed future study.

Conclusions

In Lemo, ILSSI proposed maximizing SSI of high-value, dry-season crops, using shallow groundwater and one of five alternative water-lifting technologies. Analysis and simulation with integrated and interactive IDSS models enabled us to assess:

- the amount of land appropriate for the proposed SSI interventions
- the amount of irrigation water required for the proposed SSI interventions
- the complete hydrology of the watershed with and without the proposed SSI interventions
- the rate of soil erosion with and without the proposed SSI interventions
- the impact of various farming practices (such as current versus recommended fertilization application rates) on crop yields, watershed hydrology, and farm economies, when implemented in conjunction with the proposed SSI interventions
- the economic viability and nutritional benefits to typical farm families of implementing the proposed SSI interventions

IDSS simulations indicated that the proposed SSI interventions can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage, and would not compromise the environmental health of the watershed. The proposed SSI interventions would use less than 10% of the annual shallow groundwater recharge. Moreover, the proposed SSI interventions would reduce stream flow by only 5.6%, and should not compromise downstream flows.

Though the proposed SSI interventions had only a limited impact on wet-season grain yields (since irrigation was applied only to the dry-season crops), simulations predicted that dry-season onion yields would increase substantially with increased irrigation water of up to 455 mm depth (the irrigation depth resulting in 0% stress to onion crops). Similar results would be expected with respect to other dry-season crops, including fodder.

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping system) on farm-family economics in Upper Gana. These analyses compared the costs and benefits of five alternative water-lifting technologies: pulley-and-bucket irrigation, and rope-and-washer pumps operated by hand, animal, gasoline motor, and solar power. Of the alternate technologies examined, none of the technologies met the irrigation water requirements for the proposed SSI interventions (i.e., for all 540 ha of irrigable land in the kebele). Implementation of the proposed SSI interventions using gasoline motor pumps produced by far the highest NPV, NCI, and EC reserves of the six alternative scenarios simulated (including the baseline, non-irrigated scenario). The second-best-performing scenario implemented animal-powered pump irrigation, and the worst of the six scenarios simulated (including the baseline, non-irrigated scenario) was the scenario that implemented irrigation with pulley and bucket. In each of the alternative scenarios, the increase in farm revenue was due almost entirely to the sale of surplus irrigated fodder and onion. Where gasoline motor pumps were used, the forecasted sales of irrigated fodder and onion contributed, on average, 62% and 17%, respectively, of total crops receipts, and 83% and 17%, respectively, of the net cash (profit) for the five-year planning horizon.

Although gasoline-motor pumps could not irrigate all 540 ha of irrigable land in the kebele at 0% water stress, they had twice the coverage animal-powered pumps (the next-best alternative), though with much higher operational and capital costs. Individual farmers might benefit by spreading entry costs over more irrigated area, perhaps by having two or three farmers share a pump. Simulation results showed that irrigation with both gasoline motor pumps and animal-powered pumps will generate profit and income for the farmer. The lower operating, maintenance, and environmental costs of solar pumps (as opposed to gasoline-motor pumps) might also make them an attractive long-term option.

Despite improvements in farm family economics resulting from the proposed SSI interventions, nutritional deficiencies persisted under the simulated, improved cropping system. We would also, therefore, propose expanding the types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits. The evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future study.

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