Ex Ante Analysis of Small-Scale Irrigation Interventions in Bihinaayili

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1. 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 the Bihinaayili watershed, in the Savelugu-Nanton District in the Northern Region of Ghana. The annual crops yields produced in the area are far below global average yields, and this study indicated that current crop yields in the watershed are only approximately 40% of crop potential. Farm-family livelihoods are derived from main crops, such as maize, sorghum, and soybean, produced in the rainy season. Vegetables such as tomato and pepper are produced as well, and cultivation of these crops could be expanded with the implementation of SSI in the dry season; however, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

In Bihinaayili, ILSSI proposes implementing SSI, using water collected and stored in water-harvesting ponds (dugouts) along the stream networks and one of three alternative water-lifting technologies, to maximize cultivation of high-value vegetable and fodder crops in the dry season. ILSSI evaluated the proposed SSI interventions by simulating and comparing two alternative farming systems:

i. continuous cropping of rainy-season crops (maize, sorghum, and soybean), using current (minimal) irrigation; and
ii. multiple cropping of fertilized rainy-season crops (maize, sorghum, and soybean), with several irrigated, dry-season crops; and cultivation of a perennial fodder crop (e.g., Napier grass).

For purposes of the simulations, APEX and FARMSIM chose tomato, pepper and fodder (oats/vetch) as representative irrigated dry-season crops, 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 ample water available for the proposed SSI interventions in the Bihinaayili watershed. Because dugouts were used to collect and store water subsequently used for dry-season irrigation, the proposed SSI interventions affected both the amount and the timing of the stream flows in the Bihinaayili watershed. Simulations indicated that the proposed SSI interventions would reduce average monthly stream flow by 37%, reduce peak flows, and increase low flows. The decrease in average monthly stream flows may have negative impacts on downstream social-ecological systems; however, the decrease in peak flows, the increase in low flows, and a reduction in sediment influxes may have positive implications for upstream and downstream social and ecological systems. The dugouts used to store irrigation water will be susceptible to siltation, however, and dredging sediment loads from the dugouts to the fields will be a challenging task.

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizers and irrigation could double crop yields in the Bihinaayili watershed. The implementation of multiple-cropping systems also affected simulated crop yields and sediment losses. Proper understanding and use of multiple-cropping combinations could increase crop yields and improve soil health, but some combinations would probably decrease productivity. For the fertilizer application scenarios simulated in this study, multiple cropping of maize or sorghum with pepper or tomato resulted in significant increases in simulated maize and sorghum yields, but decreases in simulated pepper and tomato yields. Multiple cropping of maize or sorghum with fodder significantly increased simulated maize and sorghum yields and did not significantly affect fodder yields. In contrast, multiple cropping of soybean with dry-season crops did not significantly affect simulated yields of soybean or the dry-season crops.

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping systems) on farm-family economics in Bihinaayili village. These simulations also compared the costs and benefits of three alternative water-lifting technologies: pulley-and-bucket irrigation; diesel-pump (both rented and owned) irrigation; and solar-pump irrigation. In all, six scenarios (including the baseline, non-irrigated scenario) were simulated. The scenarios that implemented multiple cropping of soybean (rather than maize) with diesel- and solar-pump-irrigated dry-season crops produced by far the highest net present value, net cash farm income, and ending cash reserves of the scenarios simulated (including the baseline, non-irrigated scenario). In contrast, the scenarios that included multiple cropping of maize with diesel-pump-irrigated dry-season crops and multiple cropping of soybean with pulley-irrigated dry-season crops did not differ greatly from the baseline, non-irrigated scenario.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies in iron persisted under the simulated, improved cropping systems. 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.

Further 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 simulation and field research.

2. Introduction

Agriculture is the most important economic sector in Ghana, employing more than half of the population on a formal and informal basis and contributing a quarter of the gross domestic product and export earnings (Heintz 2005). The agriculture sector is largely subsistence-based, and suffers from low and erratic rainfall which lowers crop yields. The country remains a major net importer of agricultural food products (Ashitey and Rondon 2012). Modernizing agriculture is one of the goals of Ghana's agriculture policy, with the principal objective of increasing farm productivity. Just as the adoption of science-based technology during the 1970s propelled Asia from famine to regional food surplus within 25 years (Hazell 2009; Djurfeldt et al. 2005), investment in agriculture and reform of agricultural policy, technology, and management practices could be the surest path to food self-sufficiency and could spur faster overall economic growth in Ghana. However, as in other parts of the world, farming systems in Ghana are complex and changes can have unintended consequences. For example, SSI and other agricultural interventions could have adverse environmental effects such as soil erosion, loss of plant nutrients, and changes in watershed hydrology. Increased reliance on SSI 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 may or may not prove economically beneficial.

ILSSI was formed to undertake research aimed at increasing food production, improving nutrition, accelerating economic development, and contributing to environmental protection in Ethiopia, Ghana and Tanzania. There are three major components of ILSSI: (1) field studies evaluating selected SSI methods; (2) household surveys to assess the 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 proposed SSI interventions 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 four 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 the Bihinaayili watershed, in the Savelugu-Nanton District in the Northern Region of Ghana. The dramatic shift in rainfall that occurs between the rainy season and the dry season restricts rain-fed cropping to the rainy season. Annual crops yields produced in the district are far below global average yields, and this study indicated that current crop yields in the Bihinaayili watershed are only approximately 40% of potential yields. Major factors contributing to low crop production include erratic weather conditions, low soil fertility, and ineffective management practices.

Information about the area'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 SWAT, APEX and FARMSIM was the typical farming system currently used by farmers in the region. It consisted of main crops (maize, sorghum, and soybean) grown during the main rainy season, using current (minimal) irrigation. The proposed SSI interventions simulated with SWAT used water collected and stored in water harvesting ponds (dugouts) to enable multiple cropping of the rainy-season crops (maize, sorghum, or soybean) with several irrigated, dry-season crops. All three models simulated application of improved fertilizer rates on the rainy-season crops and cultivation of certain perennial crops (e.g., Napier grass). APEX also simulated multiple cropping of unfertilized, rainy-season crops as a means of assessing the impact of increased fertilization rates. Details of the farming systems simulated with SWAT and APEX are given in Appendices A1 and A2, respectively. FARMSIM was used to simulate the effects on farm-scale economics of the proposed SSI interventions, as well as three alternative water-lifting technologies.

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.

3. Materials and Methodology

3.1. Site description

The Bihinaayili watershed is located 9°34’28.53” N, 0°50’16.05” W in the Savelugu-Nanton District in the Northern Region of Ghana (fig. 1).

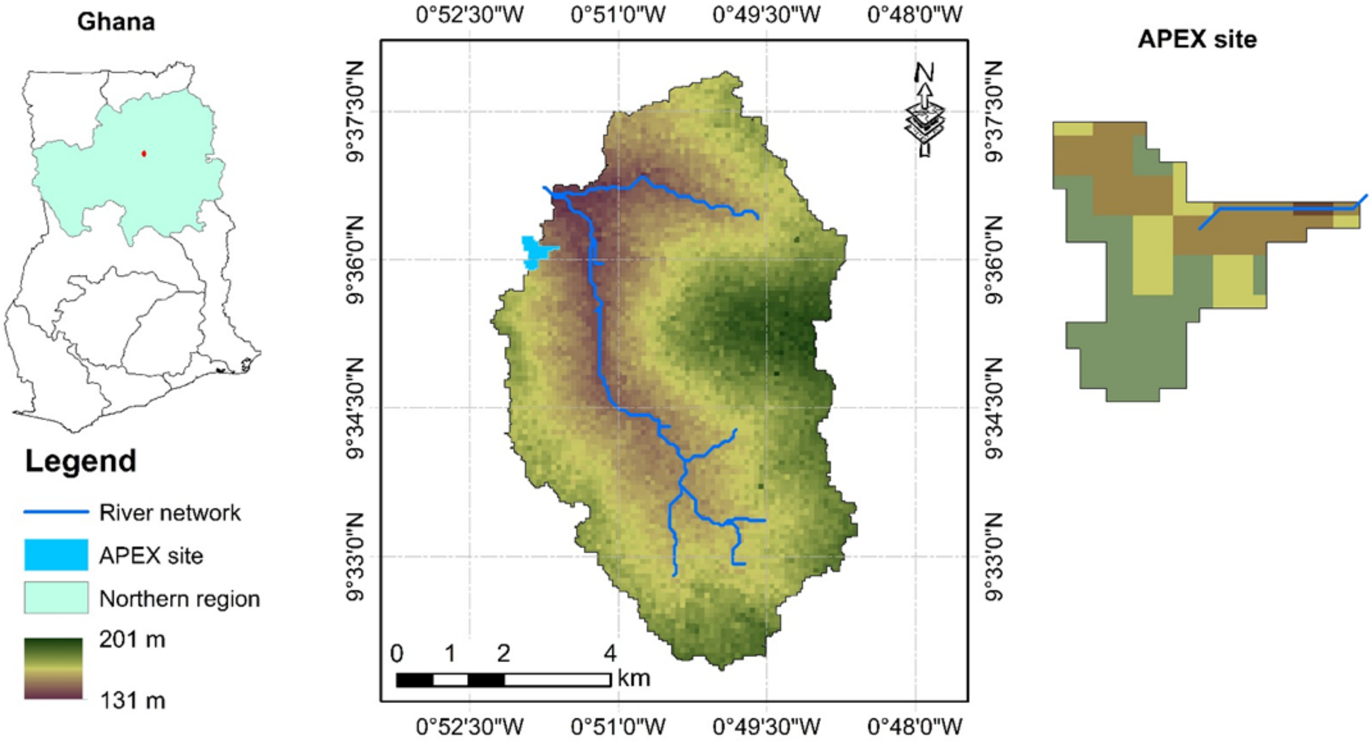


Figure 1. Bihinaayili watershed boundary, main streams and Subarea 53, simulated with APEX.

The watershed covers a 4,897.35-ha area, is characterized as nearly level to gentle slopes, with elevations ranging from 131 meters above mean sea level (mamsl) to 201 mamsl. The average percent slope of the watershed, computed from 30m-resolution Enhanced Shuttle Land Elevation Data from NASA’s Shuttle Radar Topography Mission (SRTM), is approximately 4%. Four types of land use were identified in the Bihinaayili watershed: agricultural land (55%), forestland (33.95%), pasture land (4.24%)

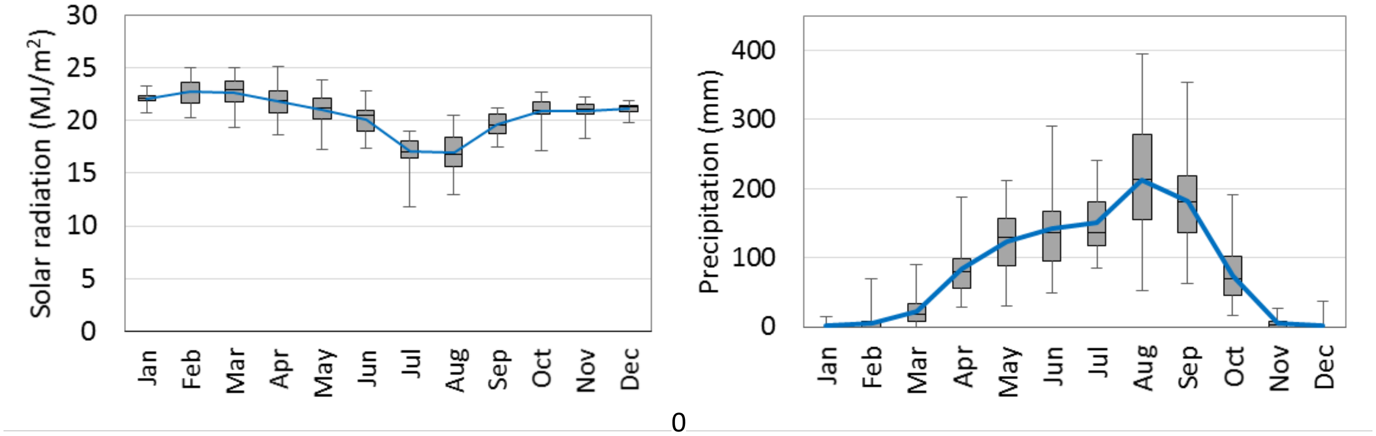
and wetland (6.03%) (USGS EarthExplorer). Water covers 0.78% of the watershed (USGS EarthExplorer). Only one soil type, loamy-sand soil, was identified in the watershed.

Unlike southern Ghana, where year-round rainfall allows for multiple cropping seasons, the Northern region has two distinct seasons: a prolonged dry season from November to March, which is usually accompanied by severe water shortages; and a wet season from April to September. For the period from 1980 to 2010, the average annual rainfall was approximately 1000mm and the watershed received 70% to 80% of annual rainfall between May and September (fig. 2(b)). These weather patterns restrict rain-fed cropping to a single cropping season; therefore, irrigation may improve crop and livestock production. According to a 2015 IFPRI study, the main crops cultivated in the Bihinaayili area are maize, sorghum, rice, soya, beans, groundnut, cowpea, Bambara, beans, millet, and guinea corn, with maize and sorghum being the dominant crops.

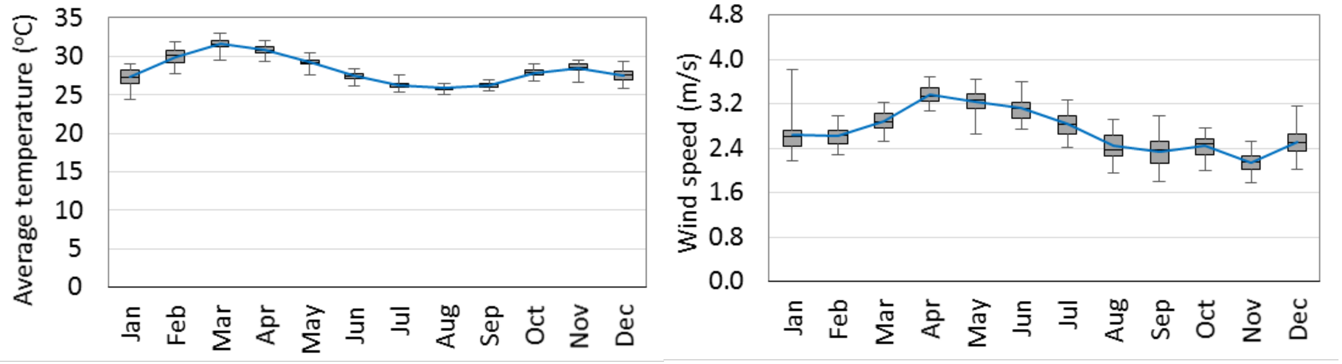
For APEX, a sub-watershed dominated by agricultural land (subarea 53, equivalent to SWAT's subbasin 53) was selected (fig 1). The sub-watershed selected for APEX is located at the outlet of the Bihinaayili watershed (fig. 1), and is approximately 22.4 ha in area, with elevations varying from 144 mamsl to 160 mamsl. The average percent slope of the sub-watershed is approximately 3.1% (USGS EarthExplorer). The soil in this subarea is comprised of 20% clay, 73% sand, and 7% silt, and is classified as sandy clay loam (Lf1-1a-1) by the FAO. The area is poorly endowed with surface water, and there are only a few seasonal streams (Osumanu 2007). Farmers in subarea 53 depend mainly on rain-fed agriculture, with a small group of farmers practicing irrigation through shallow wells and a small number of deeper wells. The dominant crops in the subarea are sorghum, maize, and soybean. The nearest village, Kogni, is the main market.

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

3.2.1. Hydro-meteorological data. Hydro-meteorological data of the study site was collected from the Ghana Meteorological Agency (GMA) via our partners at the International Water Management Institute (IWMI). Missing meteorological data was filled by Climate Forecast System Reanalysis (CFSR) data collected from the Texas A&M University Spatial Sciences website (globalweather.tamu.edu). The CFSR data was corrected by a linear bias correction to match with the long-term annual rainfall. Figure 2 shows the boxplots of the monthly average meteorological data for the watershed for the period from 1980 to 2013.



(a) Solar radiation **(b) Rainfall**



(c) Average temperature **(d) Wind speed**

Figure 2. Monthly average weather data from a synoptic station from 1980 to 2013. The rectangle represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

3.2.2 Spatial data.

a) A global land use map from Land Use Systems (LUS) Version 1.1, collected from the FAO GeoNetwork, was used to characterize the watershed. The land use map was developed by combining more than 10 global datasets, and has a spatial resolution of approximately 10 km. Land use data were also obtained from the Volta Basin Authority Geoportal (VBAG 2007).

b) A 30-m resolution Digital Elevation Model (DEM) from SRTM Enhanced Shuttle Land Elevation Data (USGS EarthExplorer) was used to characterize the watershed. The DEM voids were filled with the predecessor, 90-m resolution SRTM DEM after resampling the grid to 30-m resolution.

c) A digital soil map from the Soil and Terrain Database for Southern Africa (ver. 1.0) (FAO and ISRIC 2013) was used to extract soil properties. The soil map includes percent soil texture, organic carbon content and other relevant information at depths of 0-100 cm and 100-200 cm.

3.2.3 Stream flow data. Stream flow data for calibrating SWAT were obtained from our partners at IWMI from a river gauging station on a tributary of the White Volta.

3.2.4 Crop management data. Crop management data were obtained from agricultural specialists in the region and from the FAO Irrigation and Drainage Manual (Allen et al. 1998). Appendices A1 and A2 set forth crop management and fertilization schedules for crops in the baseline and alternative scenarios, as simulated with SWAT and APEX, respectively.

3.2.5 Crop yield data. Crop yield data for APEX calibration and validation were obtained from:

a) the Spatial Production Allocation Model (SPAM) dataset for the 2005 cycle (HarvestChoice 2014), with a spatial resolution of 10 km;

b) the FAOSTAT database (FAO 2014), including calculated crop yields aggregated for all of Ghana from 1961 to 2013 (but not including crop management practices); and

c) a 2013 survey by the International Food Policy Research Institute (IFPRI) of households in the Bihinaayili area, covering crop management practices, including fertilizer type and application rates and dates.

Table 1 shows the SPAM yields estimates for the site for the 2005 cycle and average FAOSTAT crop yields from 1983 to 2013 for maize, sorghum, and soybean.

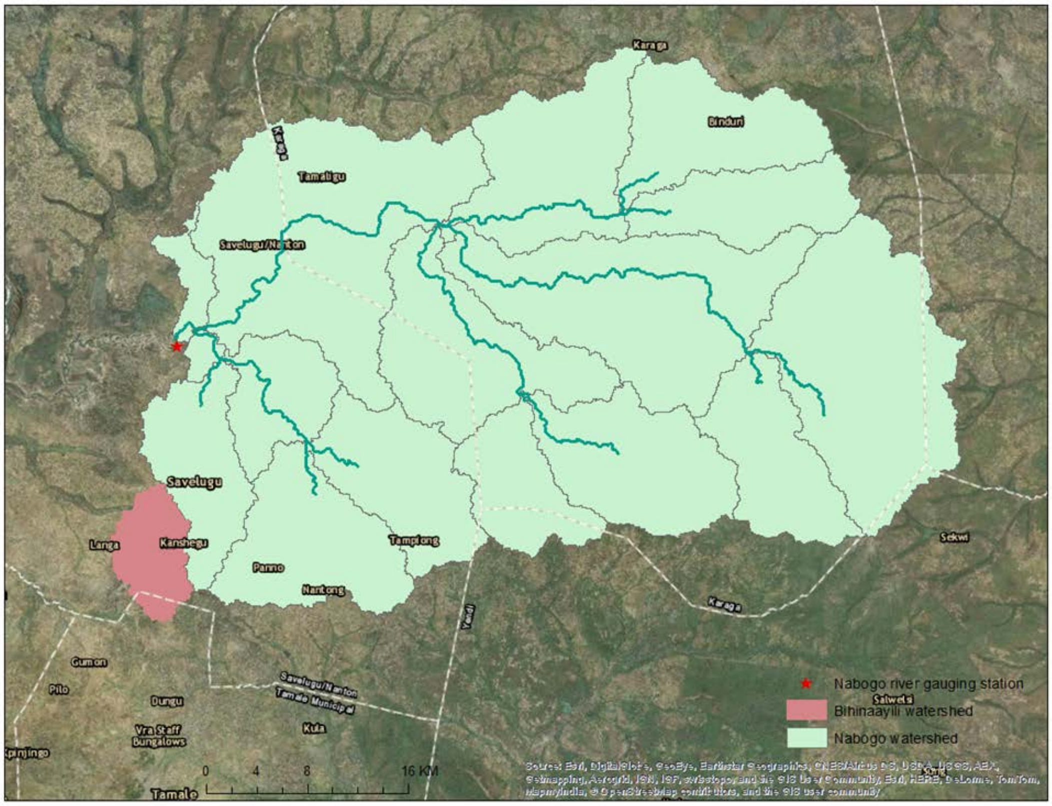
Table 1. SPAM 2005 cycle and FAOSTAT average crop yield (1983 to 2013) (t/ha)

Dataset	Country	District	Maize (t/ha)	Sorghum (t/ha)	Soybean (t/ha)
SPAM (2005)	Ghana	Bihinaayili	1.30	0.80	1.80
FAO (1981 to 2010)	Ghana	--	1.55	1.03	--

3.3 Methods

3.3.1 SWAT and APEX model setup and calibration. First, the SWAT model was set up for the entirety of the Bihinaayili watershed. The 4,897.35-ha watershed was subdivided into 236 subbasins with a mean area of approximately 20 ha, so as to accommodate small-scale agricultural water management interventions during the ex-ante analysis. SWAT further disaggregates the subbasins into smaller hydrologic response units (HRUs), lumped land areas within subbasins comprised of unique land cover, soil, and management combinations. This separation into smaller units allows the model to reflect differences in evapotranspiration and other hydrologic conditions for different land cover and soil (Neitsch et al. 2012). Five slope classes were defined, aimed at classifying areas into different levels of suitability for irrigation, based on slope requirements (Chen et al. 2010; FAO n.d.; Kassam et al. 2012; Mati et al. 2007). The slope classes were <2%, 2%-8%, 8%-12%, and >20%.

Using SWAT, flow and sediment were simulated by transferring the calibrated and validated model parameter sets from the nearby Nabogo river gauging station in the Nabogo watershed (fig. 3). The Nabogo watershed has a catchment area of 2097 km^2. For the calibrated watershed, 64.28% is forested land, 16.96% is agricultural land, 16% is wetland, and 2.76 is pasture land. There are three types of soils in the Nabogo watershed; two of the soils have sandy-clay-loam texture and the third has loamy-sand texture.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, Esri, HERE, DeLorme, TomTom, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 3. Locations of the Bihinaayili watershed and the Nabogo watershed, where the SWAT model was calibrated.

APEX was set up for identical subareas (of the same shape and size as SWAT's subbasins) to guarantee that streamflow volume and sediment yield were comparable between SWAT and APEX. The flow and sediment yield of APEX's subarea 53, as estimated by SWAT, were used to calibrate the APEX parameters. Calibration was achieved by using the automatic calibration tool APEX-CUTE (auto-Calibration and UncerTainty Estimator (Wang et al. 2014). After calibration to replicate flow and sediment yield outputs of SWAT, APEX crop parameters were calibrated to match maize, sorghum, and soybean yields of the SPAM dataset for the 2005 cycle. As validation, APEX-simulated crop yields from 1983 to 2013 were compared with FAOSTAT's calculated crop yields using standard statistical measures, including root-mean-square error and percent difference.

APEX-simulated flow and sediment were calibrated for the period from 1983 to 2013. We applied the Penman-Monteith method to estimate potential evapotranspiration, SCS Curve number for estimating runoff and the Modified Universal Soil Loss Equation (MUSLE) to estimate soil erosion. For the baseline simulation, after assigning the current management schedules (fertilization type, rates, and application dates), crops are grown year after year on the same land.

3.3.2 Alternative scenarios simulated with SWAT and APEX. Alternative scenarios simulated with SWAT and APEX included: multiple cropping of fertilized rain-fed crops (maize, sorghum, and soybean) in the rainy season with alternative, irrigated and fertilized crops in the dry season; and cultivation of certain perennial fodder crrops (e.g., alfalfa and Napier grass). In evaluating the effects of the proposed SSI interventions at the watershed scale, SWAT assumed that irrigation water would be pumped water harvesting ponds (dugouts). SWAT simulated multiple cropping of rainy-season grain crops with irrigated tomato in the dry season, and rainy-season rotations of maize/soybean and sorghum/soybean. To provide more detail at the field scale, APEX simulated: multiple cropping of each of the rainy-season grain crops with irrigated tomato, pepper, and fodder (oats/vetch) in the dry season. APEX also simulated multiple cropping of unfertilized rainy-season crops with fertilized and irrigated dry-season crops, in order to quantify the impact of improved fertilization management.

The alternative scenarios simulated with SWAT and APEX are specifically defined in sections 4.2 and 4.3, respectively. Detailed descriptions of the crop management practices for each of the crops simulated by SWAT and APEX are set forth in Appendices A1 and A2, respectively.

3.3.3 Economic Analyses. FARMSIM simulated a representative farm in the Bihinaayili community for five years to provide an economic perspective on promising SSI interventions identified by SWAT and APEX simulations. Due to the lack of household data for the Bihinaayili community, FARMSIM used household data from a 2014 survey by Africa Rising of nearby community of Duko, located in the same watershed as Bihinaayili. The survey indicates that the majority of the area's population derive their livelihoods from subsistence farming, and that the major crops grown, by area, are maize (341 ha), sorghum (99 ha) and soybean (60 ha), on an estimated total cropland of 560 ha (rain-fed and irrigated). Vegetables such as tomatoes and red pepper are produced as well (as rain-fed crops or with very minimal irrigation) on limited land. Pastureland is estimated to be about 148 ha. The main types of livestock produced are cattle, sheep, goats, and chickens. Agricultural inputs (i.e., fertilizer, irrigation, and improved seeds) are applied at very minimal levels.

In addition to the baseline scenario described above, FARMSIM simulated five different alternative scenarios involving cultivation of maize, sorghum and soybean in the rainy-season, and irrigated vegetables (tomatoes and red pepper) and fodder (oats and vetch) in the dry season, using irrigation water collected from water-harvesting ponds (dugouts). The FARMSIM simulations also considered three different water-lifting technologies that could be used to pump water from dugouts to the irrigated fields: pulley-and-bucket; diesel motor pumps (rented and owned); and solar pumps. Photos of these systems are attached as Appendix B to this report. These technologies were evaluated as to their capacity to provide necessary irrigation water to a maximum irrigable cropland of 499 ha, taking into account their varying costs and pumping rates. The pumping rate for diesel and solar pumps (40 l/min) is approximately five times the pumping rate of a hand-operated pulley-and-bucket system (8 l/min). The combination of multiple-cropping scenarios and three water-lifting technologies resulted in five alternative scenarios.

In all five alternative scenarios, maize, sorghum and soybean were cultivated in the rainy season. Because APEX simulations showed that multiple cropping of dry-season vegetables and fodder with soybean (as opposed to maize or sorghum) substantially increased vegetable and fodder yields, in four of the alternative scenarios (alts. 1, 3, 4, and 5), dry-season crops were grown on irrigable land used to cultivate soybean in the rainy season. (A portion of the acreage that had been allocated to maize in the baseline scenario was reallocated in the alternative scenarios to soybean, to enable multiple cropping of all dry-season crops with soybean.) In alternative scenario 2, the dry-season crops were grown as multiple crops with maize (instead of soybean), as a means of assessing the impacts of the soybean cropping combinations on crop production and cash profit.

In each of the five alternative scenarios, the area allocated to vegetable and fodder production was limited by the pumping capacity of the water-lifting technology employed in that scenario. The area allocated to each dry season crop increased (by equal amounts for each crop) as pumping rates (and accordingly, total irrigated acreage) increased.

In each of the alternative scenarios, the dry-season vegetable and fodder crops were irrigated as required to prevent water stress, and maize and sorghum were fertilized at improved rates (by adding 50 kg/ha of urea, in split application, and 50 kg/ha of DAP to the existing fertilizer levels). Because soybean is a nitrogen-fixing crop, it did not require additional fertilization with urea, but received an application of 50 kg/ha of DAP in each of the alternative scenarios.

A perennial crop, Napier grass, was simulated alongside the other crops in each of the alternative scenarios, but it required only minimal irrigation and its cropland area did not change across the various scenarios; accordingly, we do not discuss the crop in detail here.

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. In the model, crop production is used to meet family, seed, and livestock needs first, and any surplus is assumed to be sold. Receipts are simulated as the product of stochastic prices and residual crop and livestock production. Expenses are calculated by summing the product of hectares planted and initial costs of production from the survey. Cash expenses for the family are provided in the survey information.

To determine which of the six scenarios would be most beneficial to farm families, three types of economic indicators were calculated: net present value, net cash farm income, and ending cash reserves. Net present value is the present value of family withdrawals and the change in real net worth over a five-year planning horizon; net cash farm income equals receipts minus cash expenses; and ending cash is net cash income minus family cash expenses. The performance of the six scenarios as estimated by each of the three indicators was displayed graphically as a cumulative distribution function and as a “stoplight graph.”

4. Results and Discussion.

4.1 Stream Flow and Crop Yield Calibration.

4.1.1 SWAT calibration. The NSE and PBIAS values for the model calibration period were 0.52 and 12.7%, respectively. According to Moriasi et al. (2007), the model performance is good to satisfactory based on the NSE and PBIAS values, respectively. Figure 4 suggests that the model replicated observed stream flow values reasonably well.

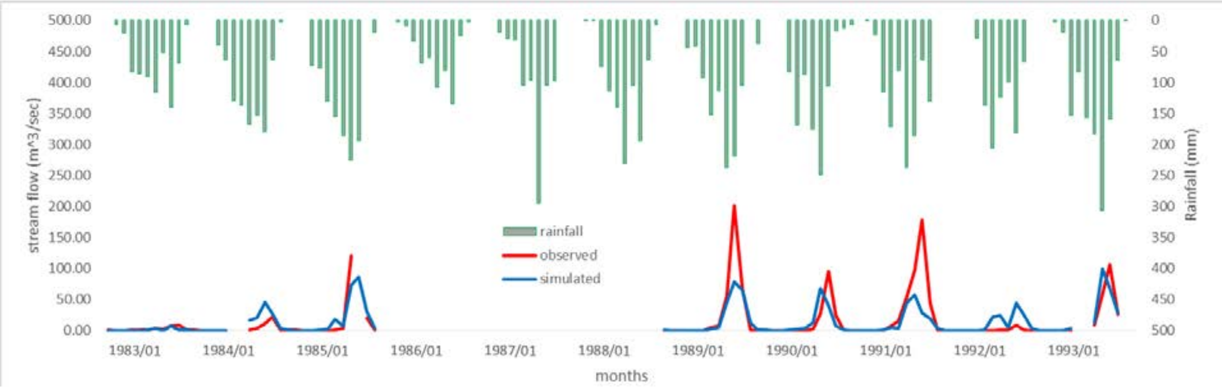


Figure 4. Hydrograph for observed vs simulated monthly stream flow for the periods where there was observed stream flow. Empty spaces, such as the period from 1986 to 1989, indicate where observed stream flow data was missing. The top axis presents observed monthly rainfall.

As figure 4 illustrates, the model did not perfectly capture peak flows. For example, the total stream flow depth in September 1989 was 248.88 mm, while the monthly rainfall in the same month was 219 mm. Rainfall in the previous months was high (e.g., 236 mm in August), and runoff depth in September possibly could be higher than in August (68.9 mm) because of a lag in stream flow across the channel; nonetheless, an increase of 265% from August to September is unlikely. Moreover, the monthly rainfall amount of 180 mm in September of 1992 barely generated observed stream flow. The mismatches in the peak flows may be related to the quality of the observed stream flow or rainfall data. Given the quality of the observed stream flow data, the model calibration was satisfactory based on the goodness-of-fit criteria. The calibrated model parameters are presented in Table 2.

Table 2. Calibrated SWAT parameters for the Nabogo watershed.

Parameter name	Fitted parameter value
R__CN2.mgt	-0.0958
V__ALPHA_BF.gw	0.469
V__GW_DELAY.gw	22.67
V__GWQMN.gw	795.60
V__GW_REVAP.gw	0.0606
V__ESCO.hru	0.911
V__CH_N2.rte	0.2499
R__SOL_AWC(..).sol	0.0734

**R_ means the existing parameter value is multiplied by (1+ a given value), and*
V_ means the existing parameter value is to be replaced by the given value.

4.1.2 APEX streamflow and sediment yield calibration. The performance of the APEX model for the streamflow and sediment yield for the calibration period was reasonably good, with a Nash-Sutcliff Efficiency (NSE) value of 0.70 and R-square value of 0.73. Figures 5 and 6 show the comparison of APEX and SWAT flow simulations. Both SWAT and APEX share input datasets for land-use, soil, elevation, weather, and crop management, and use the same methods for estimating potential evapotranspiration (Penman-Monteith), runoff (SCS Curve number method), and soil erosion (Modified Universal Soil Loss Equation, or MUSLE); however, differences in the SWAT and APEX valuations result because SWAT calculates flow at the HRU level, whereas APEX calculations are field-based, and consider the dominant land use, soil and slope of a selected subarea (here, subarea 53) rather than the unique features of each of the HRUs within a subarea.

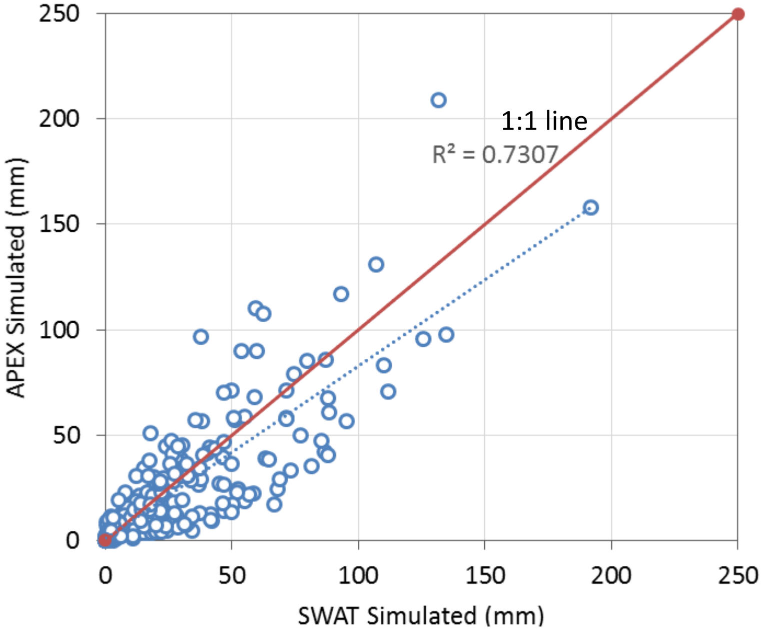


Figure 5: Scatter plot of monthly SWAT and APEX simulated flow for Bihinaayili watershed (1983-2013)

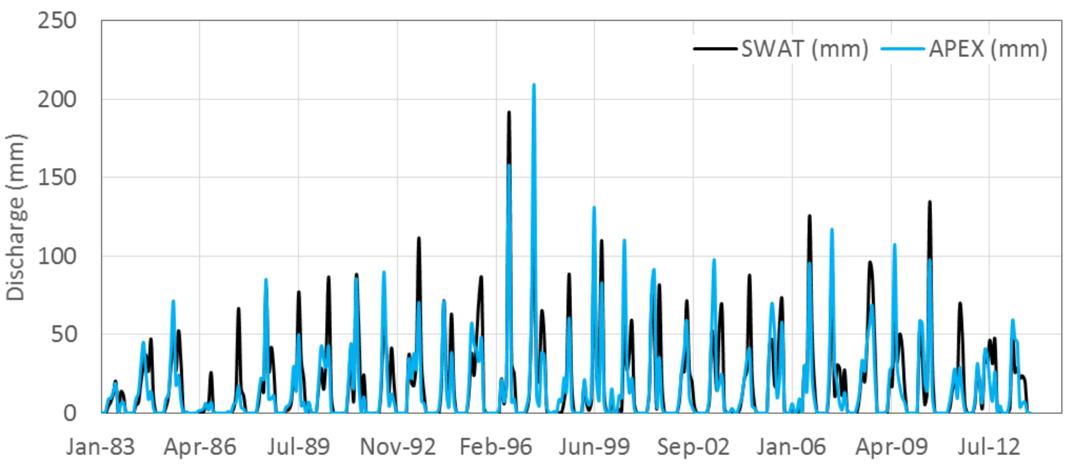


Figure 6. Monthly average SWAT- and APEX-simulated flow for Bihinaayili watershed (1983 – 2013).

The general water balance components of the watershed show evaporation and surface runoff are the dominant processes, contributing 58 and 19%, respectively.

4.1.3 Base period crop yield simulation. APEX captured the observed yields of maize, sorghum, and soybean for the year 2005 well, with a 10%, 8.6%, and 4.7% difference, respectively, from reported yields in SPAM. As a validation, simulated crop yields for the baseline were compared with the FAOSTAT calculated crop yields from 1983 to 2013.

Figure 7 shows the boxplot of APEX-simulated crop yields and FAOSTAT calculated crop yields, with the SPAM 2005 crop yields plotted as diamonds. APEX and FAOSTAT crop yields have a 7.7 and 4.5% yield difference for the study period with a RMSE of 0.41 t/ha and 0.23 t/ha for maize and sorghum, respectively.

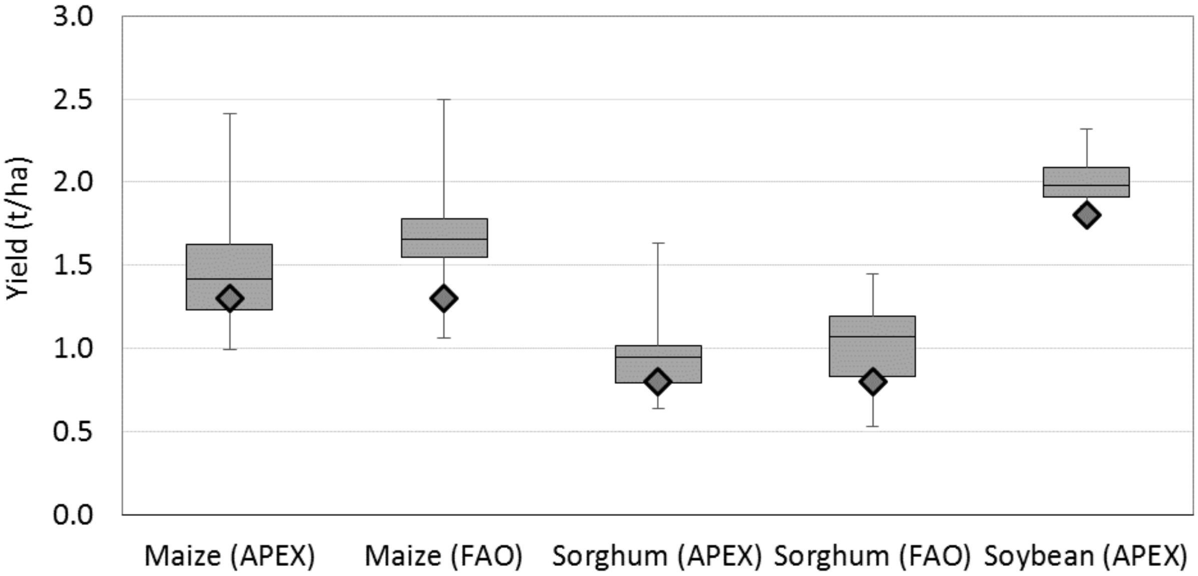


Figure 7: Comparison of APEX vs. FAOSTAT maize, sorghum, and soybean yields from 1983 to 2013, with SPAM crop yield for year 2005 represented by a diamond.

4.2 Hydrology. The proposed SSI interventions simulated with SWAT (denoted below as the “ex ante (SSI) scenario”) were:

1) on a portion of the agricultural land where the slope is less than 8%: during the rainy season, sorghum/soybean in rotation; and tomato during the dry season;
2) on the remaining portion of the agricultural land where the slope is less than 8%: during the rainy season, maize/soybean in rotation; and tomato during the dry season; and
3) on the remaining land with slopes of approximately 6% to 8%: Napier grass as a permanent fodder crop.

The total area in the watershed suitable for irrigation is 2412 ha, or 89.55% of the 2693.54 ha of agricultural land in the watershed. Tomato was cultivated on 2194.82 ha, and Napier grass on 217.26 ha. Irrigation was applied to the tomato and Napier crops whenever water stress to the crop was 25%. Detailed descriptions of the crop management practices assumed by SWAT for each of the crops simulated, including cropping schedules and fertilizer application dates and rates for both the baseline and ex ante (SSI) scenarios, are set forth in Appendix A1.

Our field research and expert opinion suggested that farmers in the Bihinaayili area construct and use water harvesting ponds (dugouts) along the stream network to collect and store for irrigation purposes water that spills over from the nearby Ligba dam. Therefore, this study uses dugouts as a source of irrigation water during the dry season. The dimensions of the dugouts (42,500 m^3) were designed to store the average annual irrigation water requirement (taking into account evaporation loss) for an average subbasin area (*cf* Dile et al. 2016). These types of dugouts can be built as community ponds and shared by a group of people who have land nearby.

4.2.1 Water resources potential. The spatial distributions of the annual groundwater and surface water resources in the Bihinaayili watershed are presented in figure 8. The simulated average annual groundwater recharge varied from 134 mm to 385 mm, and fell within the range of 325 mm to 385 mm in 83.8% of the watershed area (fig. 8). The simulated annual generated surface runoff varied from 59 mm to 220 mm, and fell within the range of 150 mm to 220 mm in 87.85% of the watershed area (fig. 8). For the Bihinaayili watershed, with a catchment area of 4,897.35 ha, the average annual volumetric groundwater recharge and surface runoff were over 16.94 million m^3 and 8.94 million m^3, respectively.

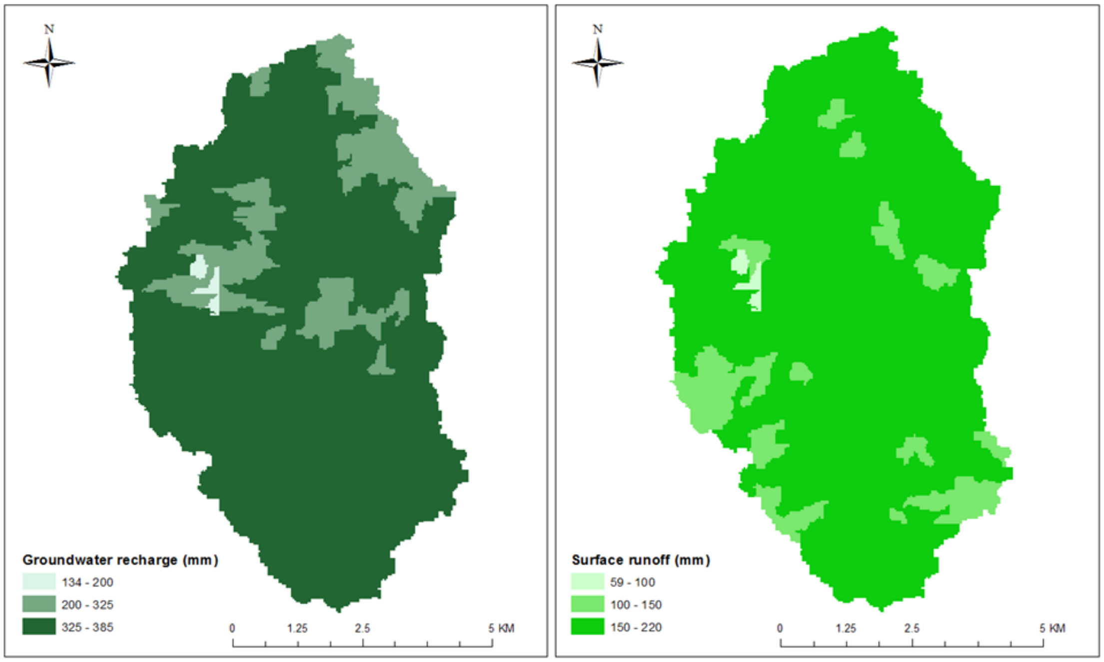


Figure 8. Water resources potential in the Bihinaayili watershed: a) average annual groundwater recharge; and b) average annual surface runoff.

4.2.2 <u>Watershed water balance impacts of the SSI (ex-ante) scenario</u>. The average annual rainfall in the Bihinaayili watershed for the period of 1980 to 2010 was 1016.7 mm. About 43% of annual rainfall was turned into stream flow, and 47% evaporated back into the atmosphere. Base flow contributed 58% of stream flow, and surface runoff contributed 42% (fig. 9).

Implementation of the ex-ante scenario using irrigation from dugouts moderately affected overall water balance dynamics. With implementation of irrigation, 42% of annual rainfall was turned into stream flow. The base flow contribution to stream flow increased to 59% and the contribution from surface runoff decreased to 41%. The ratios of percolation to rainfall and deep recharge to rainfall did not change with irrigation (fig. 9).

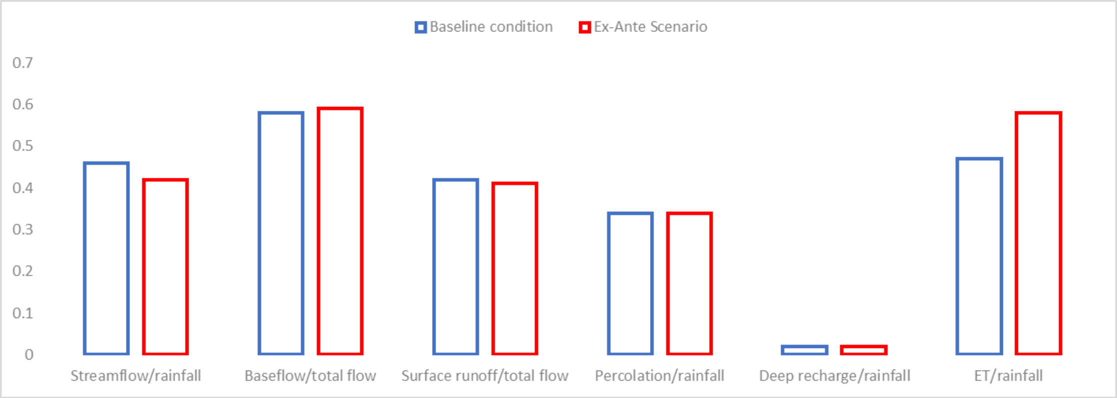


Figure 9. Water balance partitioning for the Bihinaayili watershed in the baseline scenario and ex ante (SSI) scenario.

4.2.3. Applied irrigation. Figure 10 illustrates the average annual irrigation volumes (in m^3) applied in the ex-ante (SSI) scenario of tomato and Napier grass production during the dry season and the main crop during the rainy season. The amount of irrigation water is presented in volumetric terms at the subbasin scale. Thus, the volume of irrigation water per subbasin depends on the size of the subbasin, the amount of irrigation water required in that particular subbasin, and the amount of river water available in that particular subbasin.

On irrigated fields, the spatio-temporal annual irrigation amount varied from 1 mm to 457 mm, depending on the location of the field within the watershed and the climatic year. A large portion of the irrigated area was located in the middle portion of the watershed (fig. 10). Dugouts with a total dimension of 42,500 m^3, as assumed for these simulations, provided sufficient irrigation water to the nearby irrigable fields.

In the ex ante (SSI) scenario, the average annual volume of water withdrawn for irrigation in the subbasins ranged from 322 m^3 to 62,368 m^3 (fig. 10). The total annual volume of irrigation water withdrawn was 5,099,583 m^3, or approximately 23.5% of the annual stream flow leaving the watershed.

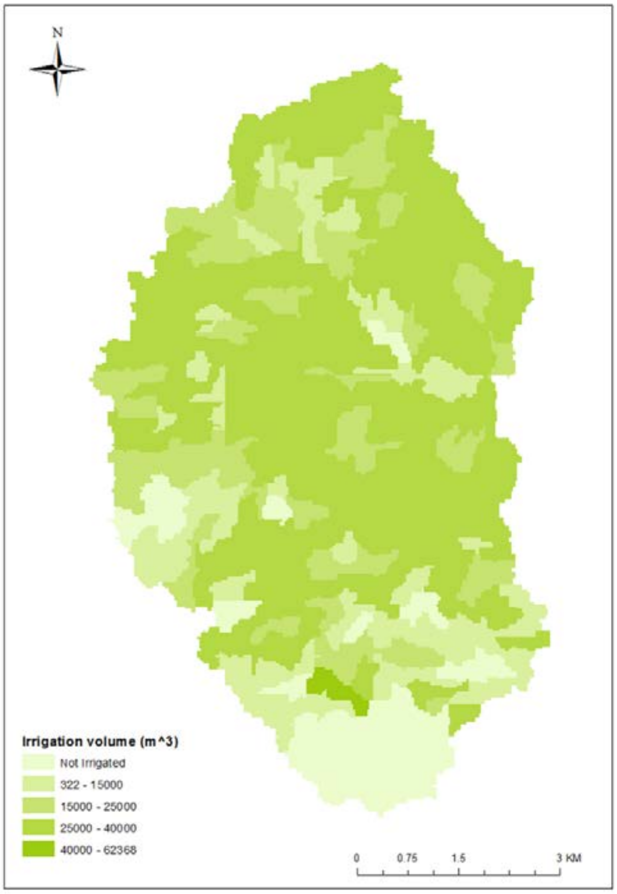


Figure 10. Average annual irrigation volumes (in m^3) for dry-season tomato and Napier grass crops and rainy-season main crop.

4.2.4 Changes in stream flows. Implementation of the proposed SSI interventions resulted in a slight reduction to the average stream flow at the outlet of the Bihinaayili watershed. In the baseline scenario, the average monthly stream flow from 1983 to 2010 was 0.67 m^3/sec. Implementation of the proposed SSI interventions during this time period reduced the average monthly stream flow by 32.7% to 0.46 m^3/sec. The stream flow hydrograph showed significant difference before and after the implementation of the proposed SSI interventions (fig. 11). Because dugouts were used to store the water subsequently used for dry-season irrigation, the proposed SSI interventions affected both the amount and the timing of the stream flow in the Bihinaayili watershed. The implementation of SSI using dugouts may moderately reduce stream flow downstream.

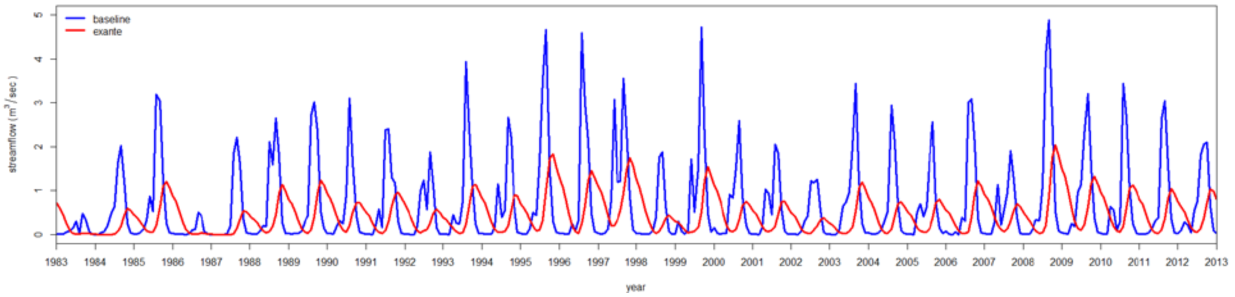


Figure 11. Stream flow at the outlet of the Bihinaayili watershed for the baseline SSI (ex ante) scenarios.

With the implementation of the proposed SSI interventions, peak flows considerably decreased, and low flows increased (fig. 12). For example, at 10% probability of exceedance, peak flow decreased by 50%, and at 90% probability of exceedance, low flow increased by 230%. The change in absolute values is higher at peak flows than low flows (fig. 12).

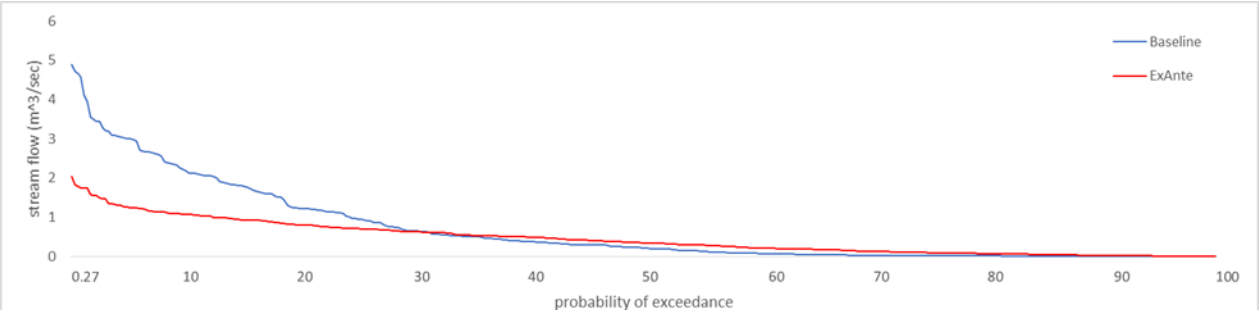


Figure 12. Flow duration curve for the monthly stream flow at the outlet of the Bihinaayili watershed in the baseline scenario and SSI (ex ante) scenario.

The decrease in total stream flow as a result of implementation of the proposed SSI interventions may have negative impacts on the downstream social-ecological systems. On the other hand, the decrease in peak flows, increase in low flows, and reduction in sediment influxes may have positive implications for upstream and downstream social and ecological systems (*cf* Dile et al. 2016). Peak flows are often associated with flooding, bank and channel erosion, and downstream reservoir sedimentation problems, which affect distribution and abundance of stream biota (Smakhtin et al. 2004). By reducing peak flows, the proposed SSI interventions may reduce downstream flood risks and protect downstream habitats from disturbance. Low flows, on the other hand, provide ecological benefits such as: adequate habitat space and suitable water temperatures, dissolved oxygen, and water chemistry for aquatic organisms; soil moisture for plants; and drinking water for terrestrial animals (Dile et al. 2016; Bunn and Arthington 2002; Richter et al. 2006). An increase in low flows could provide wetted habitat and better hydraulic and water-quality conditions that can improve total primary and secondary production (Dile et al. 2016; Bunn and Arthington 2002). By trapping sediment influxes, dugouts may also reduce nutrient transport into streams and thereby improve the water quality of the streams, while also reducing downstream problems such as the eutrophication of lakes and river reaches (Dile et al. 2016) and the siltation of lakes and reservoirs (Dile et al. 2016). Nonetheless, siltation of the dugouts will be a daunting phenomenon (Dile et al. 2016; Tamene et al. 2006), and dredging sediment loads from water-harvesting ponds to fields will be a challenging task.

4.3 Alternate scenarios simulated with APEX. The analyses that follow reference APEX baseline and alternative scenarios 1-6, summarized below with more detail given in Appendix A2. The baseline and six alternative scenarios simulated by APEX are specifically defined as follows:

> Baseline: Maize, sorghum, and soybean are grown in the wet season with no fertilization. Tomatoes, pepper, fodder (vetch/oats) and Napier grass are grown on limited land with minimal or no irrigation. Fertilization is also minimal.
>
> Alternative scenario 1: multiple cropping of rain-fed, unfertilized maize in the rainy season with irrigated crops in the dry season (maize + tomato, maize + pepper, maize + fodder).
>
> Alternative scenario 2: multiple cropping of rainy-season, fertilized maize (using 50 kg/ha of urea, in split applications, and 50 kg/ha DAP) with irrigated crops in the dry season (fertilized maize + tomato, fertilized maize + pepper, fertilized maize + fodder).
>
> Alternative scenario 3: multiple cropping of rain-fed, unfertilized sorghum in the rainy season with irrigated crops in the dry season (sorghum + tomato, sorghum + pepper, sorghum + fodder).
>
> Alternative scenario 4: multiple cropping of rainy-season, fertilized sorghum (using 50 kg/ha of urea, in split applications, and 50 kg/ha DAP) with irrigated crops in the dry season (fertilized sorghum + tomato, fertilized sorghum + pepper, fertilized sorghum + fodder).
>
> Alternative scenario 5: multiple cropping of rainy-season, fertilized soybean (using 50 kg/ha DAP) with irrigated crops in the dry season (fertilized soybean + tomato, fertilized soybean + pepper, fertilized soybean + fodder).
>
> Alternative scenario 6: continuous cultivation of alfalfa and Napier grass as perennial crops with supplemental irrigation.

An illustration of cropping schedules for the simulated crops, and detailed descriptions of the crop management practices for each of the crops simulated (including cropping schedules, and fertilizer application dates and schedules), are set forth in Appendix A2.

4.3.1 Crop yields

Alternative scenario 1. Figure 13 indicates the yields of rain-fed maize simulated as a continuous crop and in a multiple-cropping system with pepper, fodder, and tomato. Multiple cropping of maize with pepper, fodder, and tomato (as opposed to continuous cropping of maize) decreased the nitrogen stress days for the maize crop from 74 days per year to 69, 50, and 69 days per year, respectively; consequently, maize yield increased by 16.5%, 140.2%, and 43.8% when planted with pepper, fodder, and tomato, respectively. The simulation also indicated that fodder (vetch + oats) was under high temperature stress for an average of 50 days per year, which affected the water use efficiency of the fodder. Fodder also enriched soil nitrogen, consequently increasing soil nitrogen content for the maize crop.

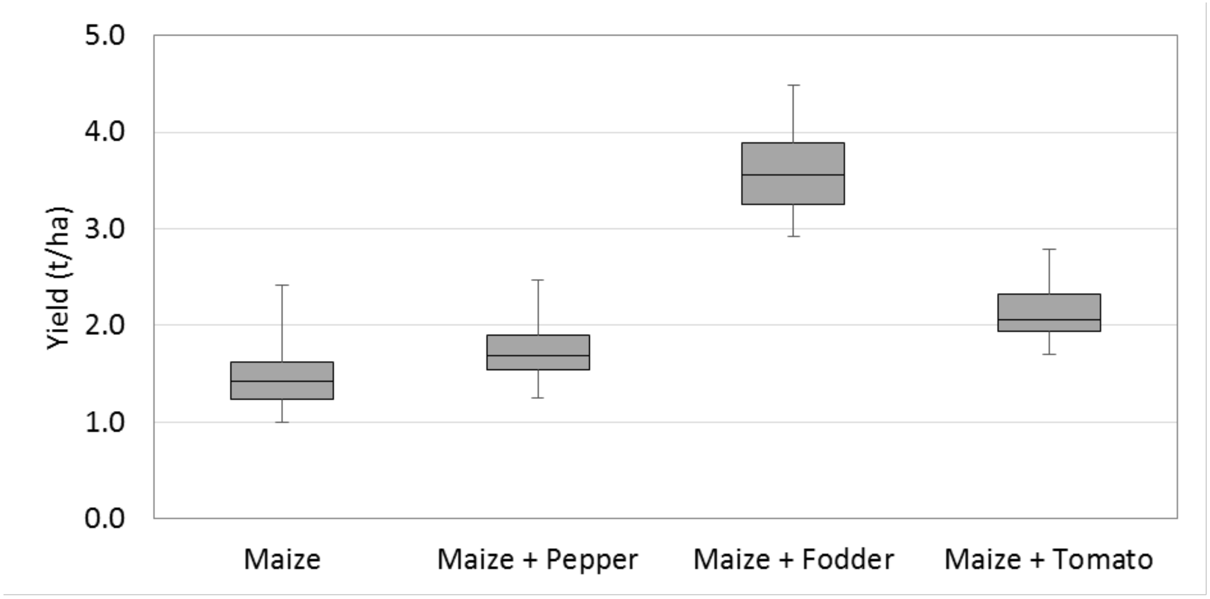


Figure 13. Maize yields when continuously cropped and when grown as a multiple crop with pepper, fodder, and tomato (from 1983 to 2013). In this figure and all of the figures included in Section 4.3, the rectangle box represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

Alternative scenario 2. In alternative scenario 2, we simulated rain-fed maize with the addition of 50 kg urea and 50 kg DAP, when grown in a continuous-cropping system and in a multiple-cropping system with irrigated dry-season crops of pepper, fodder, and tomato. The results of the simulation are depicted in figure 14. Addition of the fertilizer reduced the number of nitrogen stress days by 27% and increased the yield of continuously cropped maize by approximately 110% (as compared to yield of unfertilized, continuously cropped maize); even with the added fertilizer, maize remained under nitrogen stress, indicating that additional applications of urea could further increase the crop yield. Multiple cropping of fertilized maize with pepper, fodder, and tomato reduced the nitrogen stress days and consequently increased maize yields by 20%, 67%, and 27%, respectively, compared to the continuously cropped, fertilized maize yield (fig. 14).

Figure 14. Continuously cropped, unfertilized maize yield, compared with yields of continuously cropped, fertilized maize, and fertilized maize grown in a multiple-cropping system.

Alternative scenario 3. Figure 15 indicates the yields of rain-fed sorghum grown in a multiple-cropping system with irrigated dry-season crops of pepper fodder, and tomato. Multiple cropping of sorghum with pepper, fodder, and tomato (as opposed to continuous cropping of sorghum) decreased the nitrogen stress on the sorghum crop by 12%, 33%, and 16%, respectively; consequently, sorghum yield increased by 16.3%, 140.9%, and 43.5% when planted with pepper, fodder, and tomato, respectively.

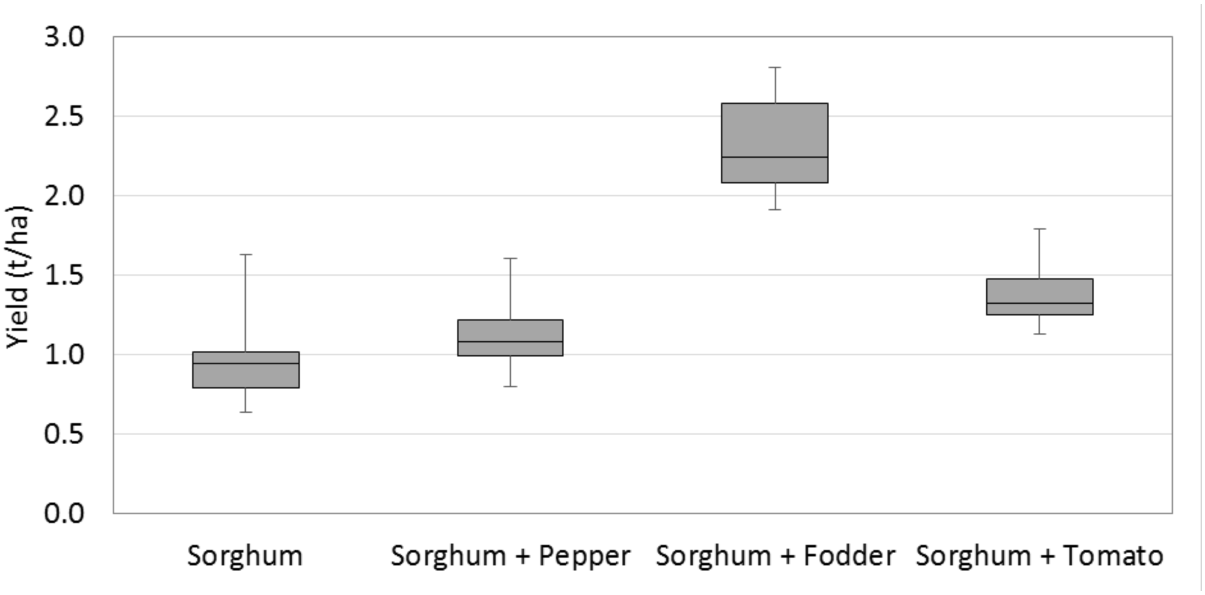


Figure 15. Sorghum yields when continuously cropped and when grown as a multiple crop with pepper, fodder, and tomato (from 1983 to 2013).

Alternative scenario 4. In alternative scenario 4, we simulated rain-fed sorghum with the addition of 50 kg urea and 50 kg DAP, when grown in a continuous-cropping system and in a multiple-cropping system with irrigated dry-season crops of pepper, fodder, and tomato. The results of the simulation are depicted in figure 16. Addition of the fertilizer reduced nitrogen stress on the sorghum crop by 33% and increased the yield of continuously-cropped sorghum by 120%. Multiple cropping of fertilized sorghum with pepper, fodder, and tomato increased sorghum yields by 19%, 66%, and 28%, respectively, compared to the continuously-cropped, fertilized sorghum yield (fig. 16).

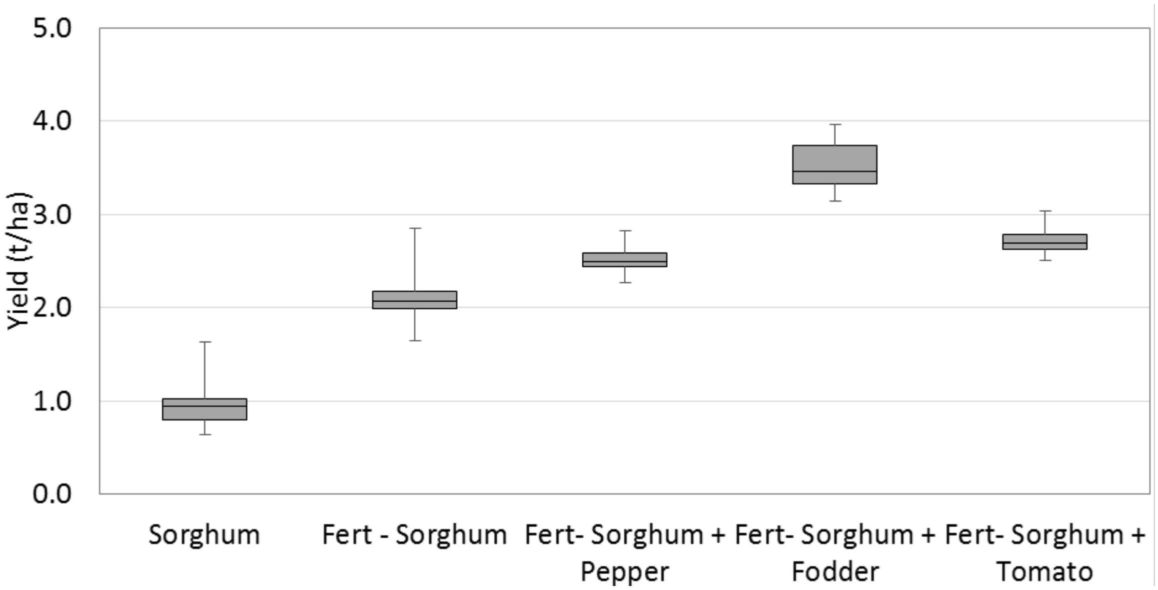


Figure 16. Continuously cropped, unfertilized sorghum yield, compared with yields of continuously cropped, fertilized sorghum, and fertilized sorghum grown in a multiple-cropping system.

Alternative scenario 5. In alternative scenario 5, we simulated rain-fed, fertilized soybean grown in a continuous-cropping system and in a multiple-cropping system with irrigated dry-season crops of pepper, fodder, and tomato. The results of the simulation are depicted in figure 17. Unlike maize and sorghum, soybean was able to obtain its own nitrogen through nitrogen fixation, so only DAP (50kg/ha) was applied. Because continuous simulation of soybean does not create significant nitrogen and phosphorus stress, the multiple cropping of soybean with pepper, fodder and tomato does not change soybean yield (fig. 17).

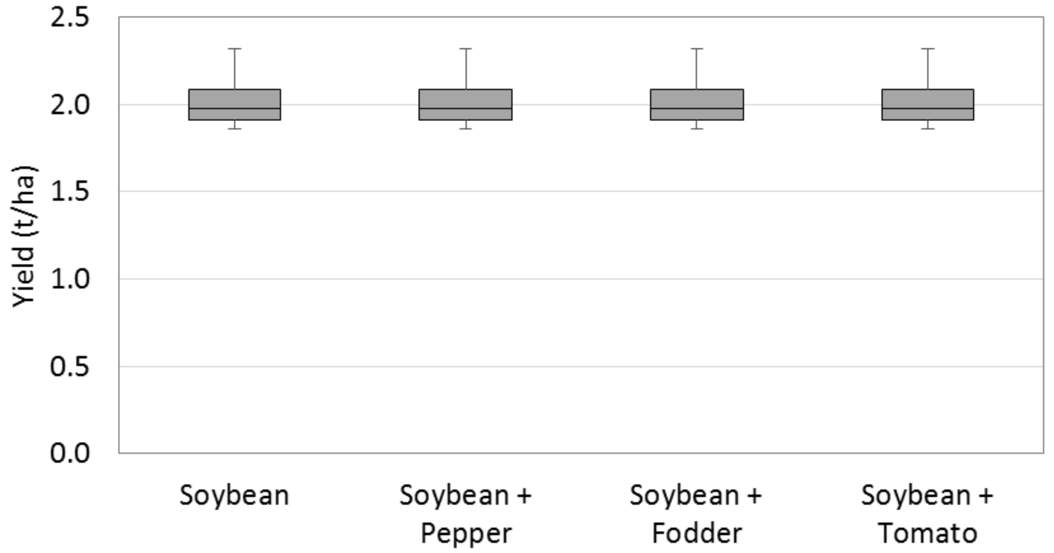


Figure 17. Fertilized soybean yields when continuously cropped and when grown as a multiple crop with pepper, fodder, and tomato (from 1983 to 2013).

The simulated yields of dry-season, irrigated, alternative crops, when planted continuously and as multiple crops with rain-fed maize, sorghum, and soybean, are shown in figures 18, 19 and 20. In addition, pepper and tomato were simulated as continuously-planted, rain-fed crops. Simulated yields of pepper grown as a continuous, irrigated crop in the dry season were 71% lower than simulated yields of pepper grown as a continuous, rain-fed crop in the rainy season. Continuously-planted, dry-season pepper suffered from high temperature stress but did not suffer any nutrient stress, whereas multiple cropping of dry-season pepper with rainy-season maize and sorghum increased nitrogen stress levels on the pepper crop and subsequently reduced pepper yields by 13% and 10%, respectively. Multiple cropping of dry-season pepper with soybean did not result in a statistically significant yield difference.

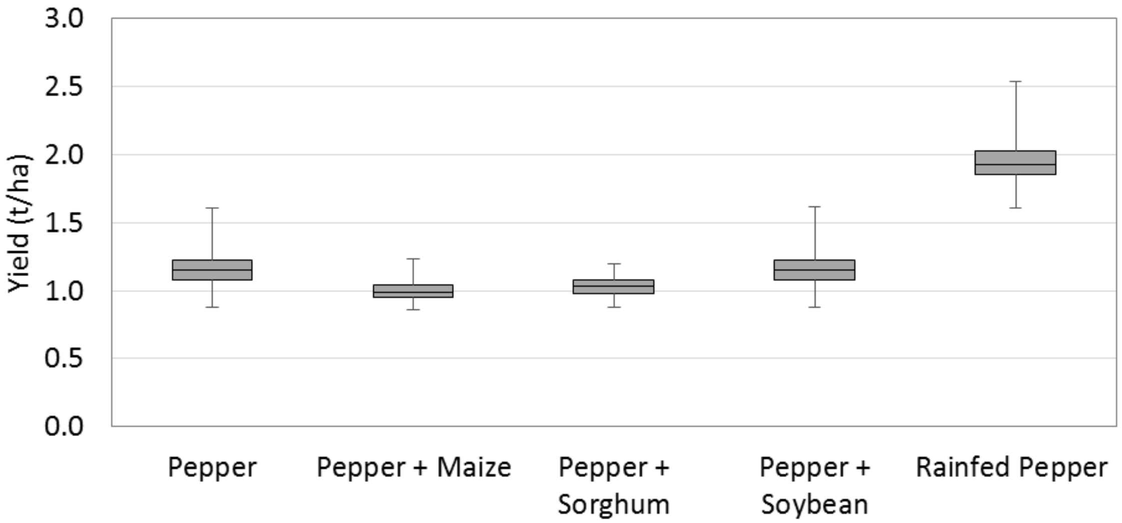


Figure 18. Pepper yield when continuously cropped (both as an irrigated, dry-season crop and as a rain-fed crop in the rainy season), and when grown as a multiple crop with maize, sorghum, and soybean (1983 to 2013)

Figure 19 shows simulated fodder yields, when simulated as a continuous crop and as a multiple crop with maize, sorghum, and soybean. Temperature was the major factor controlling fodder yield. The high temperature stress for oats was approximately 44 days, or more than half of the growing season. Multiple cropping of fodder with maize, sorghum and soybean does not show a significant yield difference.

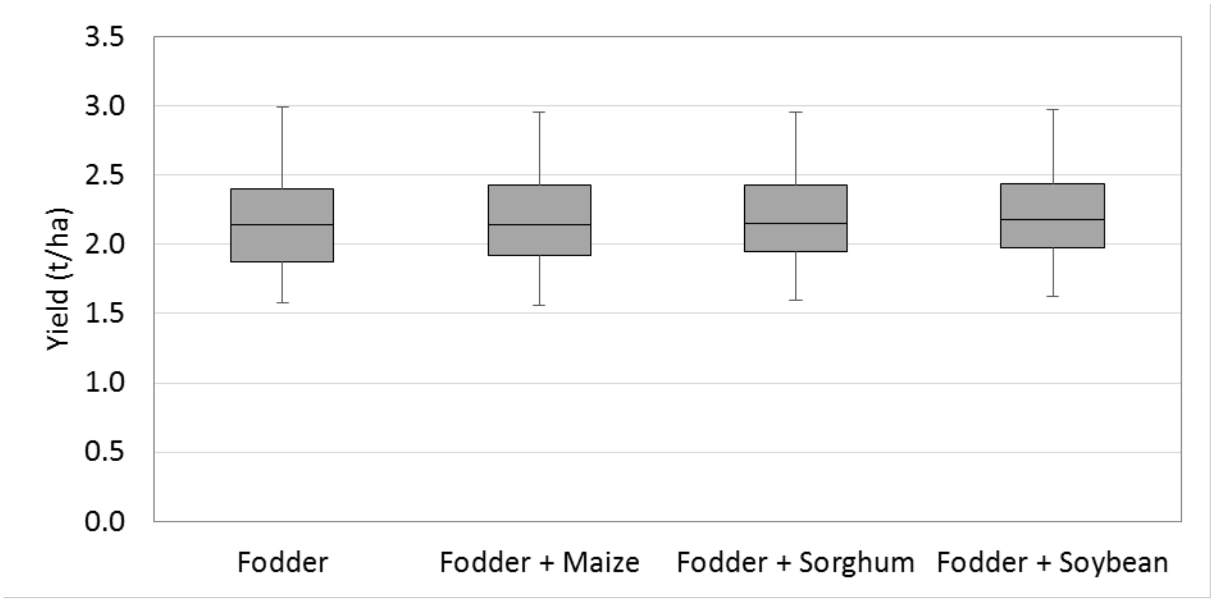


Figure 19. Fodder yield when continuously cropped, and when grown as a multiple crop with maize, sorghum, and soybean (1983-2013)

Figure 20 shows simulated yields of tomato when grown as: a continuous, irrigated dry-season crop; a multiple crop with rain-fed maize, sorghum, and soybean; and a continuous, rain-fed crop.

Continuously-cropped tomato suffered from high temperature stress, and was also under nitrogen stress for an average of 35 days per year. When tomato was simulated as a multiple crop with maize and sorghum, nitrogen stress days for the tomato crop increased by 90% and 91%, respectively, and tomato yields declined by 60% and 62%, respectively. In contrast, simulated tomato yield increased by 5.6% when grown as a multiple crop with soybean. The simulation does not indicate a statistically significant difference between continuously-cropped, irrigated, dry-season tomato and continuously-cropped, rain-fed tomato.

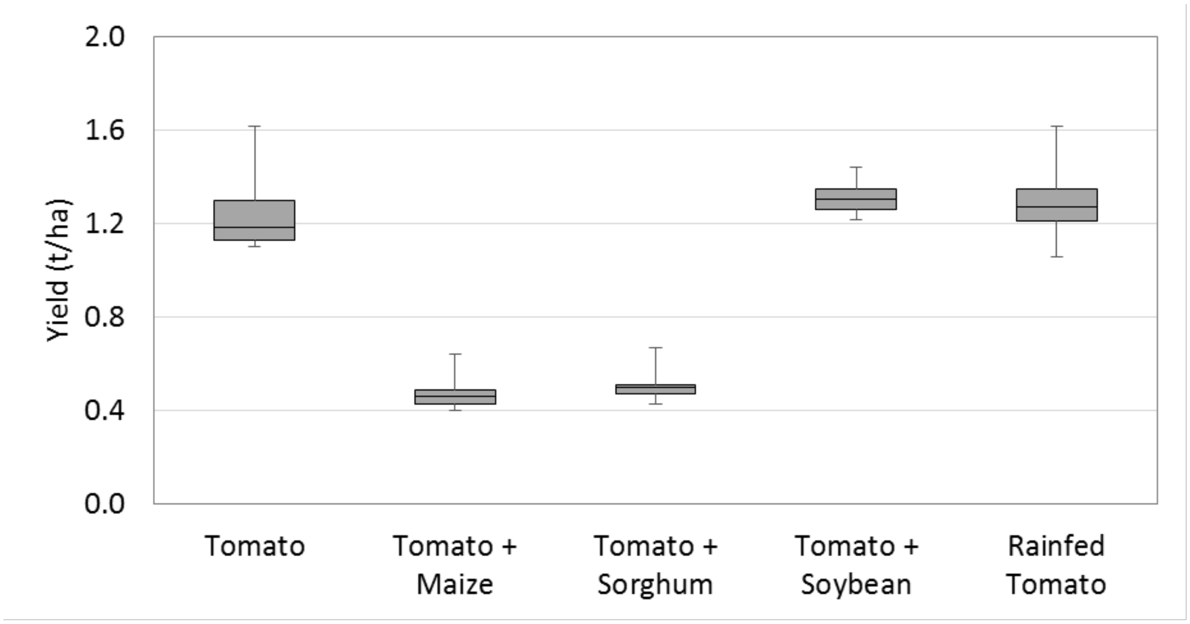


Figure 20. Tomato yield when continuously cropped (both as an irrigated, dry-season crop and as a rain-fed crop in the rainy season), and when grown as a multiple crop with maize, sorghum, and soybean (1983-2013)

Alternative scenario 6. In alternative scenario 6, alfalfa and Napier grass were planted as perennial crops, with supplemental irrigation applied in the dry season. Irrigation was applied to fill the root zone soil moisture to field capacity, and a maximum annual irrigation volume of 800 mm was budgeted. The first alfalfa harvest was scheduled after 6 months, with a subsequent cutting every 60 days over 5 years before replanting. The first Napier grass harvest was scheduled 3 months after planting, followed by cutting every 60 days for 3 years before replanting. Figure 21 shows the forage yields (t/ha) for alfalfa and Napier grass. Napier yield was limited by high temperature, water and nitrogen stress. On average, Napier was stressed for 19, 31, and 95 days per year for high temperature, water and nitrogen, respectively. Alfalfa was stressed only for temperature, for an average of 106 days per year. Simulated alfalfa yield was reasonable compared to the experimental yield conducted at the University of Cape Coast Research Farm (Bonsu and O 1997).

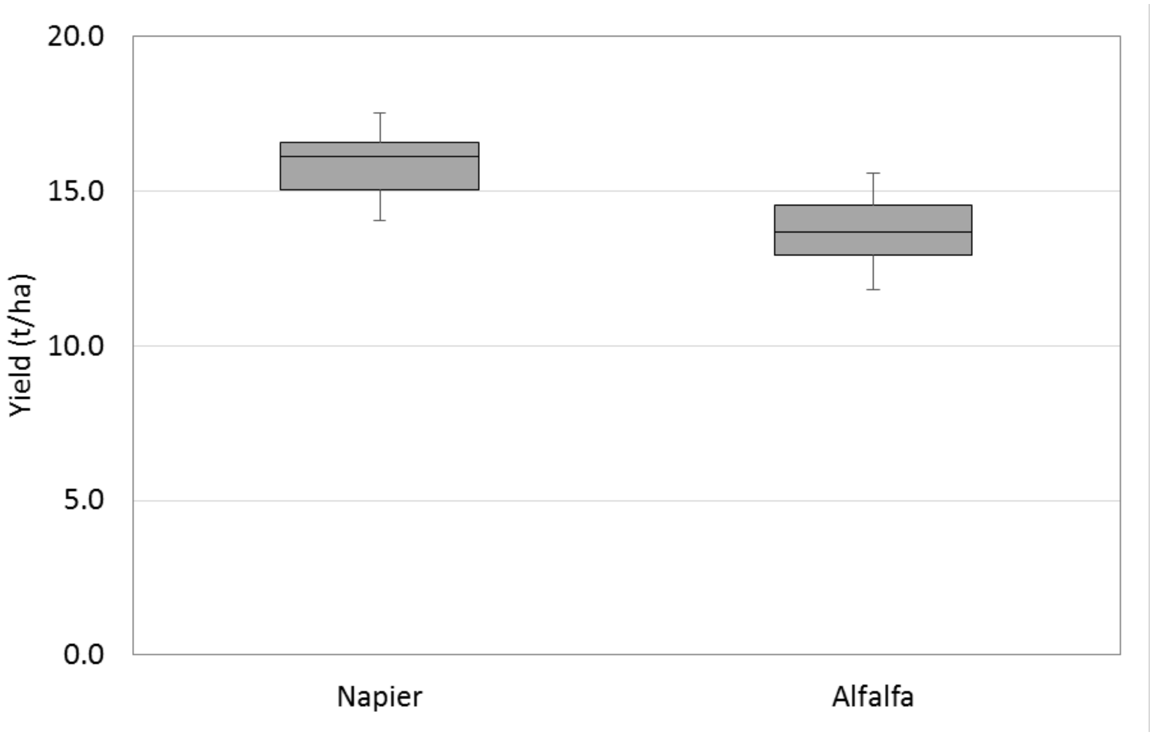


Figure 21. Yields of Napier grass and Alfalfa as perennial crops (1983 to 2013)

4.3.2 Runoff and sediment yields

Alternative scenarios 1 and 2. The effects of alternative scenarios 1 and 2 on runoff are shown in figure 22. In both scenarios, multiple cropping of maize (whether unfertilized or fertilized) did not change runoff yield at a p-value of less than 0.05 (fig. 22).

Figure 22. Runoff in alternative scenarios 1 and 2

The effects of alternative scenarios 1 and 2 on sediment yields are plotted in figure 23. Sediment yields for the baseline period from 1983 to 2013 ranged from 1 to 17 t/ha. Simulated sediment yields were 20% lower when continuously-cropped maize was fertilized, because application of fertilizer to continuously-cropped maize improved the crop's leaf area and biomass, thereby reducing rainfall erosivity. Simulations indicated that multiple cropping of fertilized and non-fertilized maize with dry-season, irrigated crops would not change the sediment yield at a p-value of 0.05, probably due to soil loss in the irrigation season.

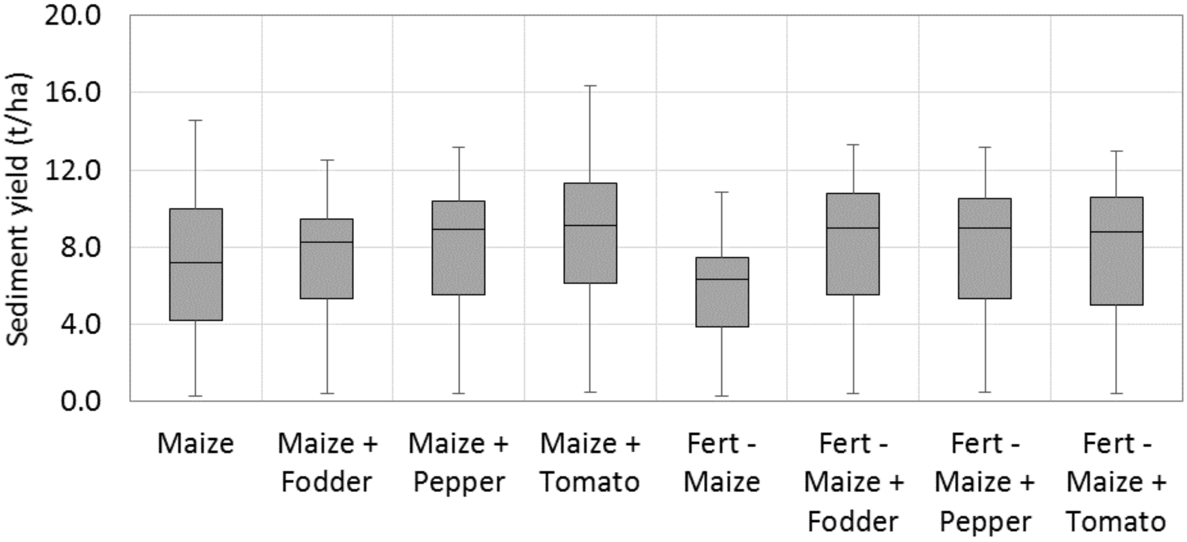


Figure 23. Sediment yields in alternative scenarios 1 and 2

Alternative scenarios 3 and 4. Figure 24 shows runoff yields in alternative scenarios 3 and 4. In both scenarios, multiple cropping of sorghum (whether fertilized or unfertilized) with irrigated fodder, pepper, and tomato did not change runoff yields at a p-value of less than 0.05 (fig. 24).

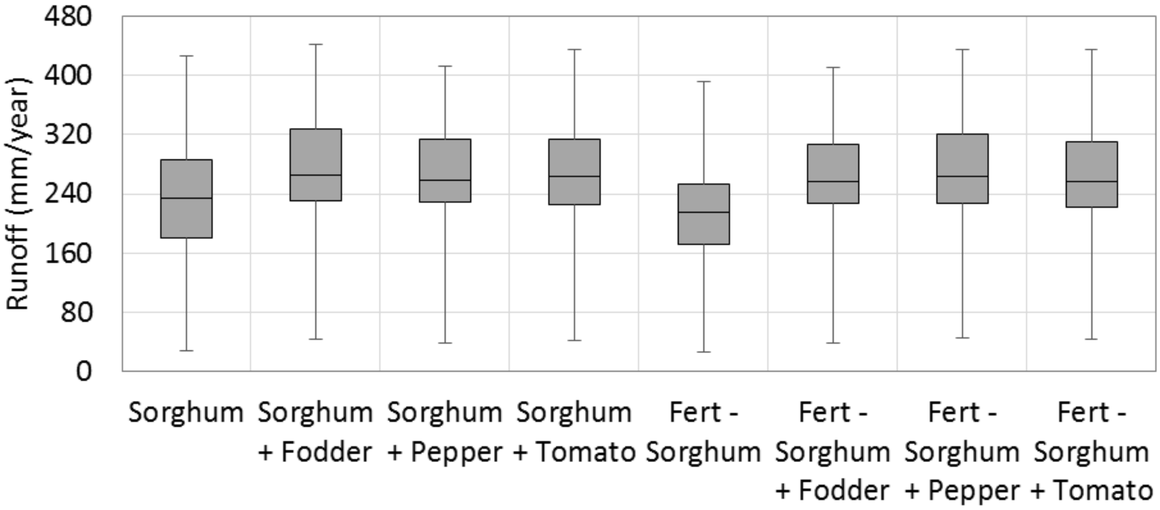


Figure 24. Runoff in alternative scenarios 3 and 4

Figure 25 illustrates the effects of alternative scenarios 3 and 4 on sediment yields. In scenario 3, multiple cropping of unfertilized sorghum with pepper increased the sediment yield (as compared to the yield of continuously-cropped, rain-fed sorghum) by 24% (fig. 25). In scenario 4, multiple cropping of fertilized sorghum with fodder and pepper increased sediment yields by 26% and 20%, respectively (fig. 25).

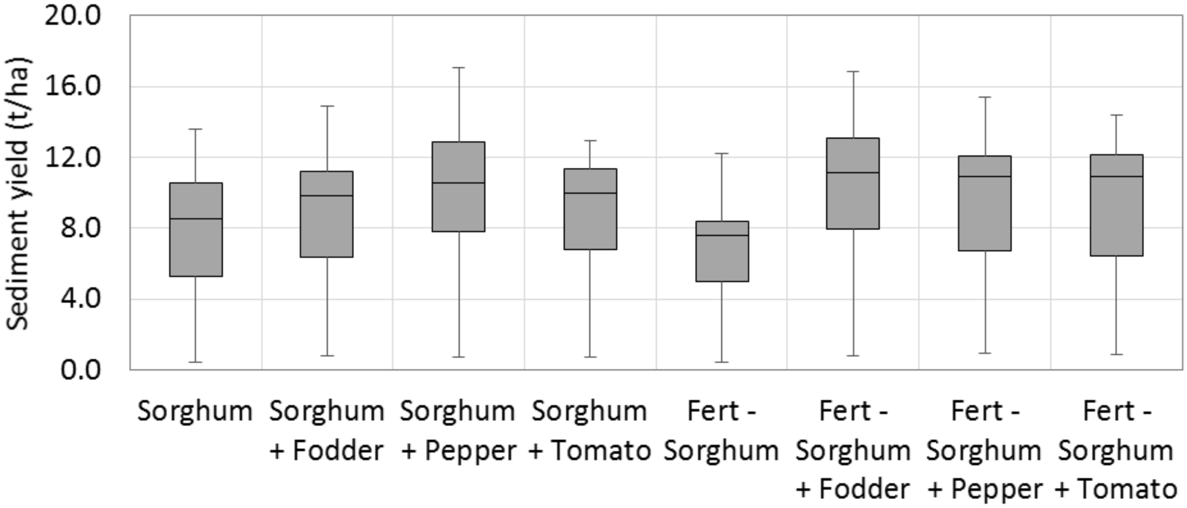


Figure 25. Sediment yield in alternative scenarios 3 and 4

Alternative scenario 5. The effects of alternative scenario 5 on runoff and sediment yield are shown in figures 26 and 27. Multiple cropping of soybean with irrigated fodder, pepper and tomato did not change runoff at a p-value of less than 0.05 (fig. 26); however, multiple cropping of soybean with irrigated fodder, which has a relatively shorter growing season, increased simulated sediment yield by 39% (fig. 27).

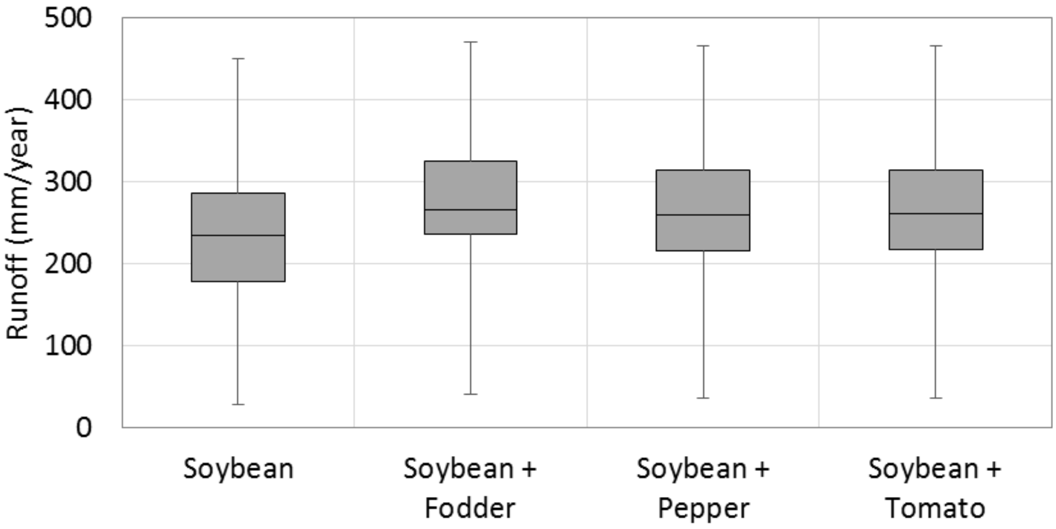


Figure 26. Runoff in alternative scenario 5

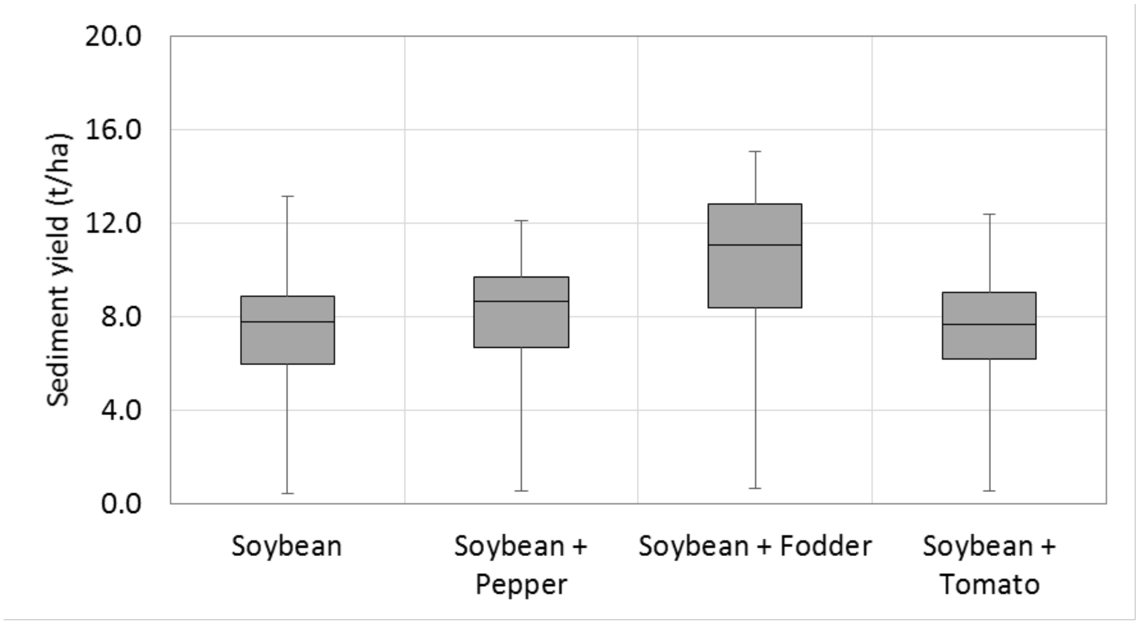


Figure 27. Sediment yield in alternative scenario 5

Alternative scenario 6. APEX simulations indicated that continuous cropping of alfalfa and Napier grass would reduce soil erosion by 98% and 88%, respectively, compared with the baseline continuous maize scenario (data not shown). Simulations indicated that alfalfa would reduce runoff by 51% compared to the baseline crop of continuous maize, but that Napier grass would not reduce the runoff significantly at a p-value of less than 0.05 (fig. 28), probably because the Napier crop was less healthy than the alfalfa crop as a result of higher water, temperature and nitrogen stress.

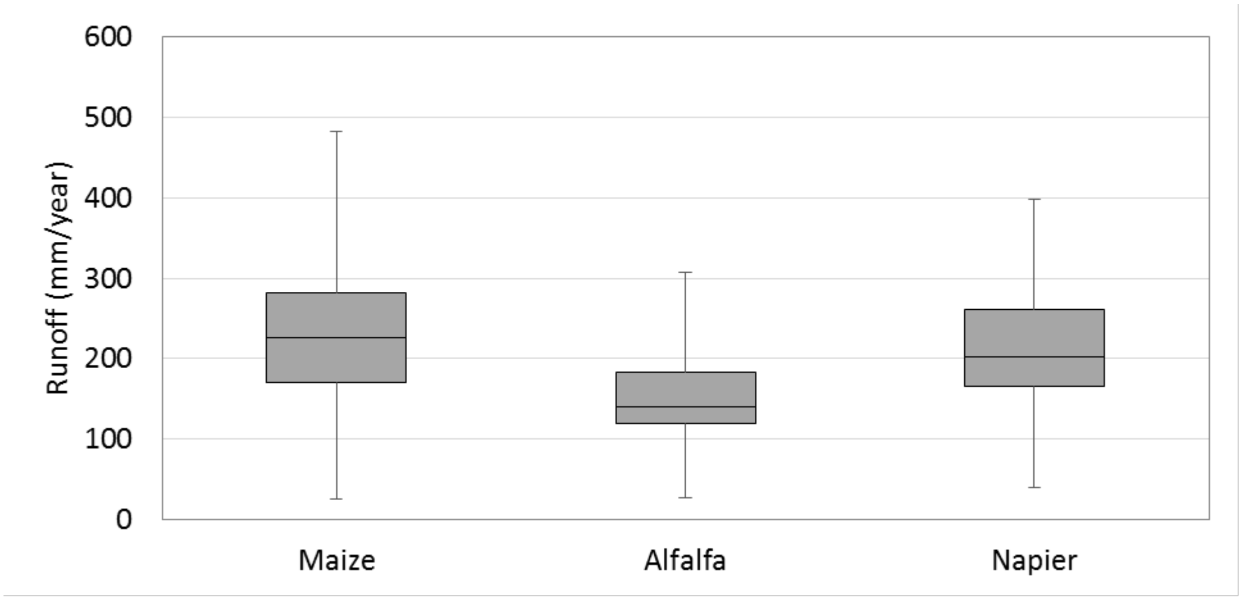


Figure 28. Runoff yields of alternative scenario 6 compared with baseline scenario

4.4 Economic analyses. The analyses that follow reference the baseline scenario and FARMSIM alternative scenarios 1-5, discussed in some detail above. The baseline scenario and five alternative scenarios are specifically defined as follows:

> Baseline (current fertilizer + no irrigation): Maize, sorghum and soybean are grown in the wet season. Tomato, pepper, fodder (vetch/oats), and Napier grass are grown on limited land with minimal irrigation. Fertilization is also minimal.

In each of the alternative scenarios (alts. 1-5), maize, sorghum and soybean are grown in the wet season and fertilized at improved rates. In addition, irrigation with one of three different water-lifting technologies (as specified below) enables cultivation of dry-season vegetables and fodder on land cultivated with either soybean or maize (as specified below) in the rainy season:

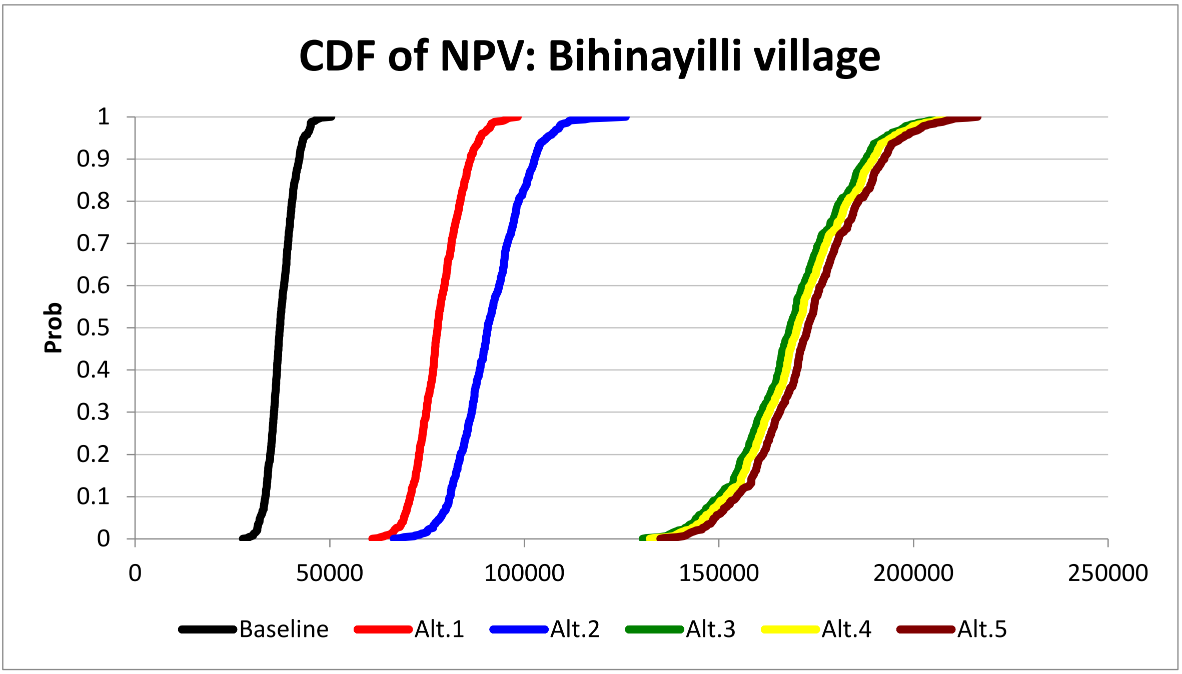
> Alt. 1: pulley irrigation + multiple cropping of soybean with vegetables/fodder + recommended fertilizers
>
> Alt. 2: rented, diesel-pump irrigation + multiple cropping of maize with vegetables/fodder + recommended fertilizers
>
> Alt. 3: rented, diesel-pump irrigation + multiple cropping of soybean with vegetables/fodder + recommended fertilizers
>
> Alt. 4: owned, diesel-pump irrigation + multiple cropping of soybean with vegetables/fodder + recommended fertilizers
>
> Alt. 5: owned, solar-pump irrigation + multiple cropping of soybean with vegetables/fodder + recommended fertilizers

Note that we did not consider a rented solar pumps as an alternative, since these systems have only recently been introduced and there was insufficient data as to rental costs. Note also that our evaluation did not include the capital costs of drilling wells or digging ponds (dugouts), as these costs can vary greatly from household to household, depending on the type of well or pond (e.g., in-field, riverine, permanent shallow well) (Namara et al. 2011). Only the capital costs related to the water-lifting technology and its operating costs were included in the model.

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 function at a competitive level with no distortion where the supply and demand determine the market prices. However, in the 5-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. Lastly, given the lack of information on cost and revenue of growing fodder in Ghana, we used information collected on the ILSSI-Ethiopia case study.

The farm-level simulation results for the six scenarios showed differences not only between the baseline and the alternative scenarios but also among the alternative scenarios in terms of net present value (NPV), net cash farm income (NCFI), and ending cash reserves (EC).

4.4.1 NPV. NPV is an indicator that assesses the feasibility and profitability of an investment or project over a certain period of time. The NPV results, as illustrated by the cumulative distribution function (CDF) graph in figure 29a, clearly indicate the importance of investing in certain methods of irrigation, fertilizers, and the multiple cropping of dry-season crops with soybean, a nitrogen-fixing crop (fig. 29a). Alternatives 3, 4 and 5 (multiple cropping of dry-season crops with soybean, using diesel- or solar-pump irrigation) showed outstanding performance, in that their CDF values lie distinctly to the right of the other scenarios for all 500 draws of the model. Of the alternative scenarios considered, alternative 2 (multiple cropping of dry-season crops with maize, using diesel-pump irrigation) and alternative 1 (multiple cropping of dry-season crops with soybean, using pulley irrigation) were the lowest-performing, although both performed considerably better than the baseline scenario. The large increase in NPV from alternative 2 to alternative 3 is attributable solely to the shift from maize to soybean, since all other conditions remain the same.



*

Figure 29a. Cumulative distribution function of NPV for Bihinaayili village

Legend

Baseline : **No irrigation**
Alt.1 : **Pulley-SV**
Alt.2 : **Diesel_PR-MV**
Alt.3 : **Diesel_PR-SV**
Alt.4 : **Diesel_PO-SV**
Alt.5 : **Solar_P-SV**

The stoplight chart below (fig. 29b) presents the probabilities in each of the six scenarios of NPV for the five-year planning horizon being less than 80,000 GH₵ (Ghanaian Cedi) (red), greater than 160,000 GH₵ (green), or between the two target values (yellow). The target values are: the average of NPV for the three lowest-performing scenarios (Baseline and Alts. 1-2) for the lower bound; and the average of the three best-performing scenarios (Alts. 3-5) for the upper bound. For a farmer in the baseline scenario, there is a 100% chance that NPV will be less than 80,000 GH₵. In contrast, for a farmer who implements alternative 3, 4, or 5 (multiple cropping of dry-season crops with soybean, using diesel- or solar-pump irrigation), there is a 0% chance that NPV will be less than 80,000 GH₵; moreover, the probability that NPV will exceed 160,000 GH₵ is 72%, 77%, and 82%, respectively. The main barrier for the best-performing scenario (Alt.5, which uses solar-pump irrigation) is the initial investment in the solar pump, which is two times higher than that of a diesel pump. However, because the long-term maintenance and environmental costs of solar pumps are much lower than those of diesel pumps, the NPV results strongly suggest that an investment in solar water-lifting technologies will pay dividends in the long run.

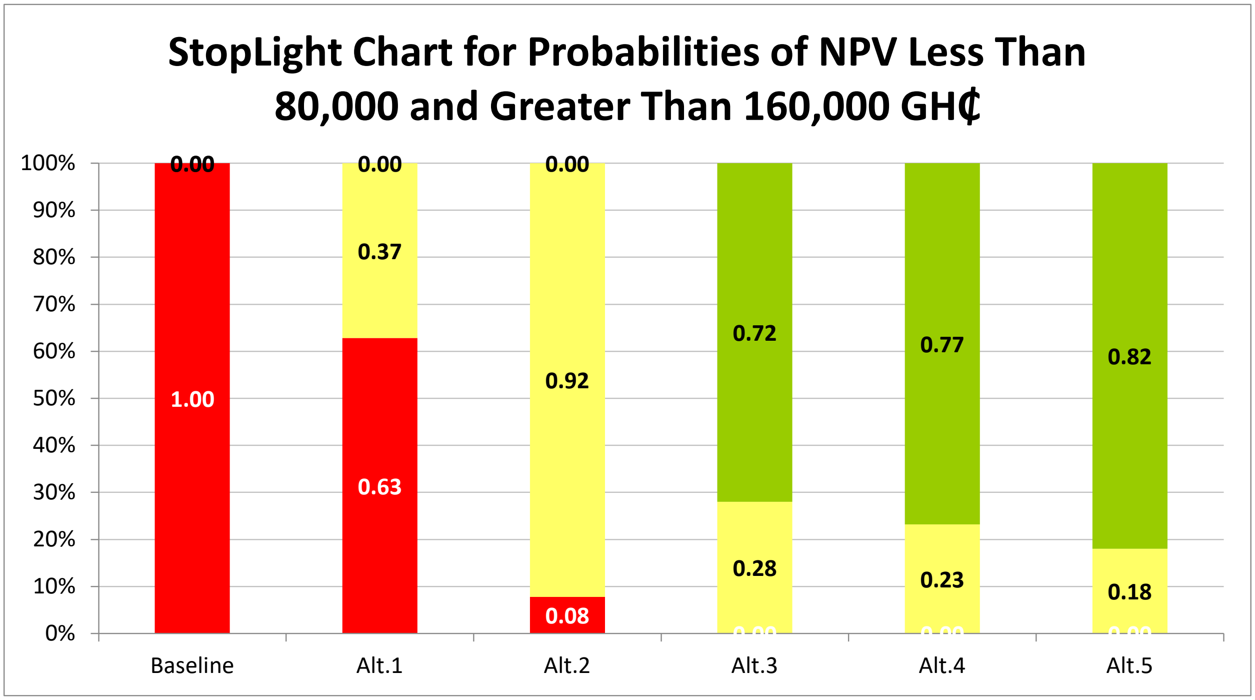


Figure 29b. Stoplight chart of NPV for Bihinaayili village

Legend

Baseline :	**No irrigation**	Alt.2 :	**Diesel_PR-MV**	Alt.4 :	**Diesel_PO-SV**
Alt.1 :	**Pulley-SV**	Alt.3 :	**Diesel_PR-SV**	Alt.5 :	**Solar_P-SV**

4.4.2 NCFI. The CDF graph for annual NCFI (fig. 30a) shows that alternatives 3, 4 and 5 (multiple cropping of dry-season crops with soybean, using diesel- or solar-pump irrigation) generated much higher NCFI than the other scenarios, as their CDF values lie completely to the right of the other scenarios for all 500 draws for the simulated farm. Of the alternative scenarios considered, alternative 2 (multiple cropping of dry-season crops with maize, using diesel-pump irrigation) and alternative 1 (multiple cropping of dry-season crops with soybean, using pulley irrigation) were the lowest-performing, although both performed considerably better than the baseline scenario. The large increase in NPV from alternative 2 to alternative 3 is attributable solely to the shift from maize to soybean production. In contrast, the choice of whether to rent or own a diesel pump (alts. 3 and 4, respectively) did not have a significant effect on NCFI.

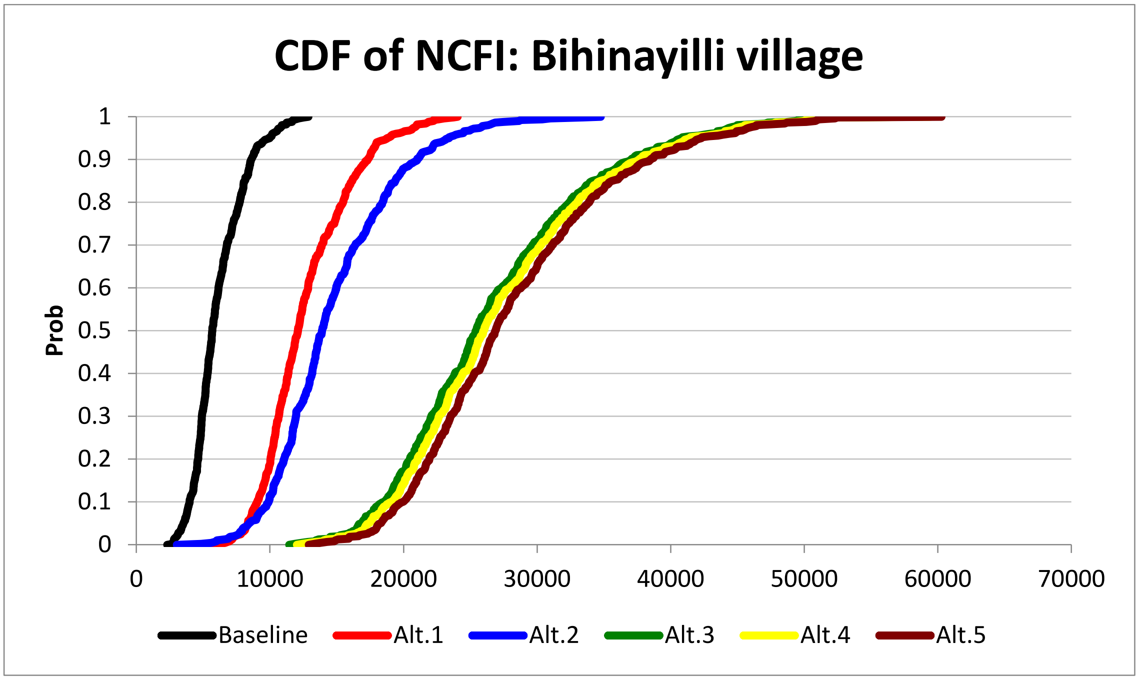


Figure 30a. Cumulative distribution function of the NCFI for Bihinaayili village

Legend

Baseline :	**No irrigation**	Alt.2 :	**Diesel_PR-MV**	Alt.4 :	**Diesel_PO-SV**
Alt.1 :	**Pulley-SV**	Alt.3 :	**Diesel_PR-SV**	Alt.5 :	**Solar_P-SV**

The stoplight chart in figure 30b illustrates NCFI in year three of the 5-year planning horizon for the baseline and five alternative scenarios. In the baseline scenario, there is an 83% chance that NCFI will be less than 8,000 GH₵, and a 0% chance that NCFI will exceed 24,000 GH₵. A farmer who adopts alternative 1 (multiple cropping of dry-season crops with soybean, using pulley irrigation) or alternative 2 (multiple cropping of dry-season crops with maize, using rented diesel-pump irrigation) has only a 3% or 4% chance, respectively, of generating NCFI of less than 8,000 GH₵, but only a 0% or 4% chance, respectively, of generating NCFI of more than 24,000 GH₵. In contrast, for a farmer who implements alternative 3, 4, or 5 (multiple cropping of dry-season crops with soybean, using diesel- or solar-pump irrigation), the probability that NCFI will exceed 24,000 GH₵ is 60%, 63%, and 68%, respectively. Note that the large jump in potential NCFI from alternative 2 to alternative 3 is attributable solely to the choice to cultivate soybean rather than maize, as all other conditions remain the same. Alternative 5 (multiple cropping of dry-season crops with soybean, using solar-pump irrigation) generated the highest NCFI.

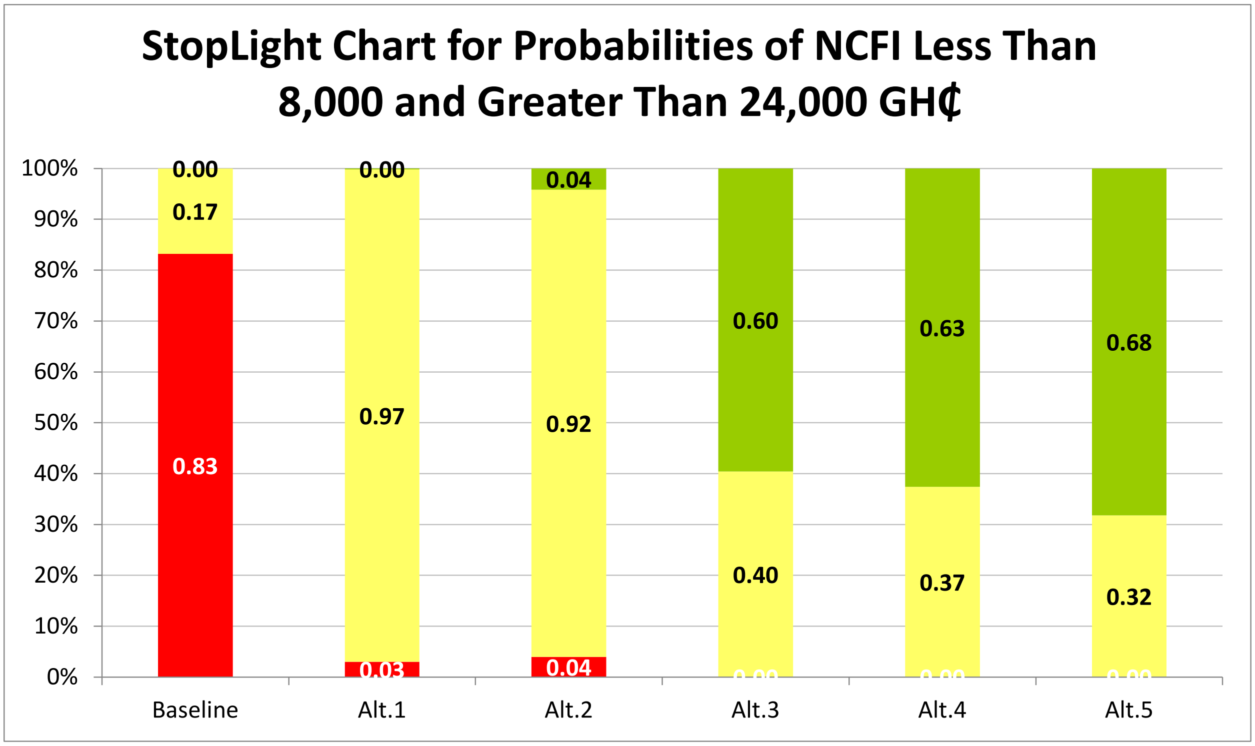


Figure 30b. StopLight chart of the NCFI for Bihinaayili village

Legend

Baseline :	**No irrigation**	Alt.2 :	**Diesel_PR-MV**	Alt.4 :	**Diesel_PO-SV**
Alt.1 :	**Pulley-SV**	Alt.3 :	**Diesel_PR-SV**	Alt.5 :	**Solar_P-SV**

4.4.3 EC. The CDF graph in Figure 31a illustrates potential EC in the fifth year of the five-year planning horizon for each of the six scenarios. The simulation results highlight once again the superior performance of alternatives 3, 4 and 5 (multiple cropping of dry-season crops with soybean, using diesel- or solar-pump irrigation), in that the CDF values for these three scenarios lie entirely to the right of the baseline scenario and alternatives 1 and 2, with alternative 5 (solar-pump irrigation) leading the group. These results suggests once again that it is worth investing in pump irrigation and improved fertilization, as well as cultivating a nitrogen-fixing crop such as soybean as a multiple crop with irrigated dry-season crops.

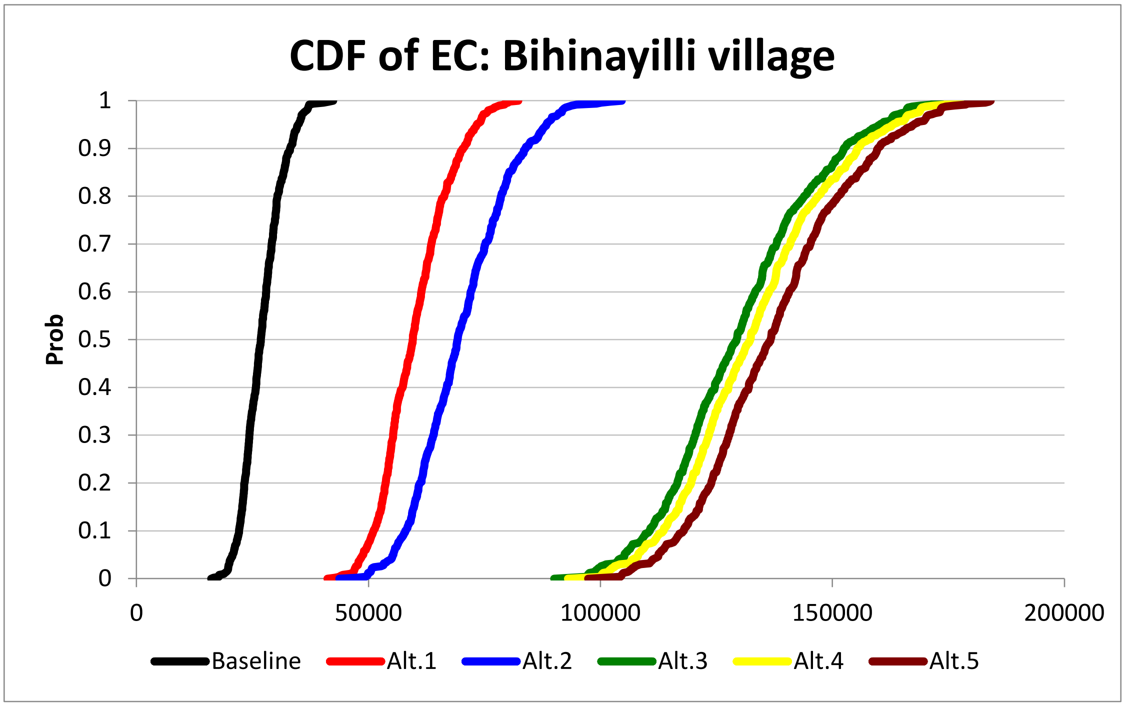


Figure 31a. Cumulative distribution function of the ending cash reserves for Bihinaayili village

Legend
Baseline : **No irrigation**
Alt.1 : **Pulley-SV**
Alt.2 : **Diesel_PR-MV**
Alt.3 : **Diesel_PR-SV**
Alt.4 : **Diesel_PO-SV**
Alt.5 : **Solar_P-SV**

The stoplight chart for EC reserves (fig. 31b) shows that, for a farmer in the baseline scenario, there is a 100% probability that EC in year five will be less than 50,000 GH₵. In contrast, for a farmer who adopted alternative 3, 4, or 5 (multiple cropping of dry-season crops with soybean, using diesel- or solar-pump irrigation), there was a 0% probability that EC would be less than 50,000 GH₵, and a 48%, 54%, and 63% probability, respectively, that EC would exceed 130,000 GH₵. Alternative 5 (solar-pump irrigation) generated the highest EC. Alternative 2 (multiple cropping of dry-season crops with maize, using diesel-pump irrigation) and alternative 1 (multiple cropping of dry-season crops with soybean, using pulley irrigation) produced much lower EC than alternatives 3, 4 and 5, although both performed considerably better than the baseline scenario.

Note: Even though the choice of whether to rent or own a diesel pump did not have a significant economic impact in terms of EC (with pump ownership resulting in only slightly higher EC during the five-year planning horizon), pump ownership would be an asset for the farmer in the long-term.

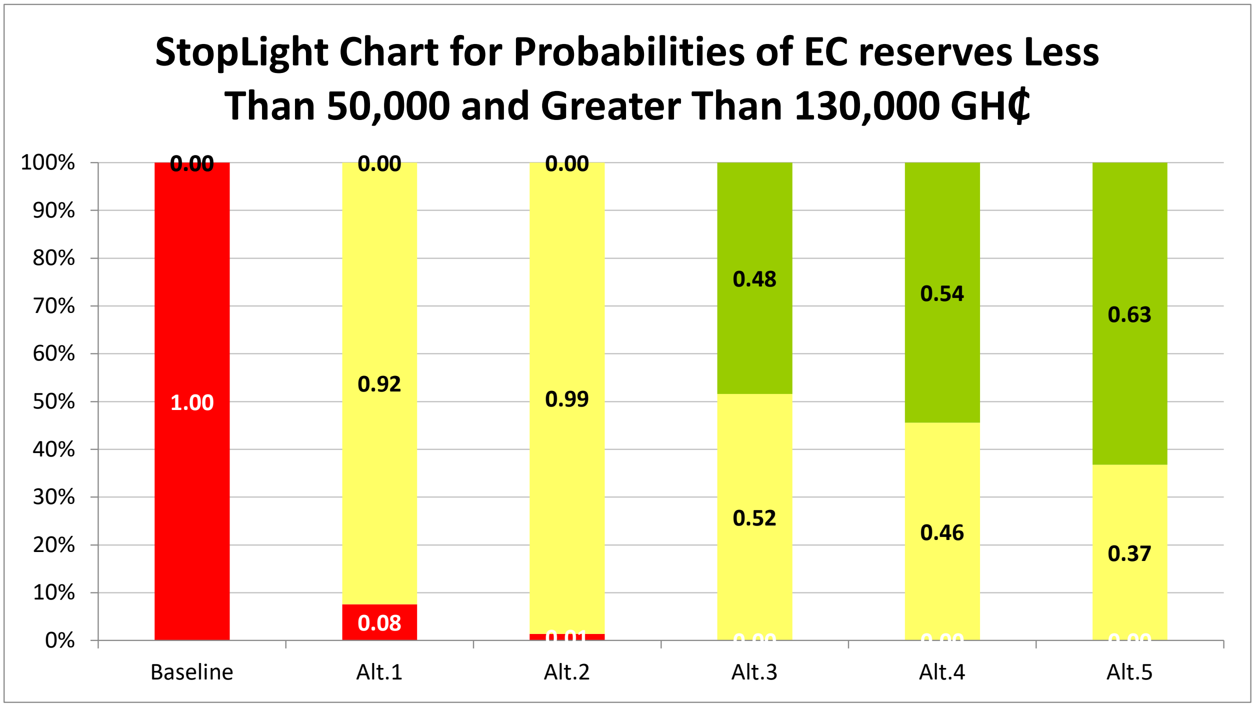


Figure 31b. Stoplight chart of EC for Bihinaayili village

Legend

Baseline : **No irrigation**
Alt.1 : **Pulley-SV**
Alt.2 : **Diesel_PR-MV**
Alt.3 : **Diesel_PR-SV**
Alt.4 : **Diesel_PO-SV**
Alt.5 : **Solar_P-SV**

4.4.4 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 type of crops grown and consumed; however, surplus food can be sold at market, and resulting revenues can be used to buy food items needed to complement nutrition requirements.

In this case, the simulation results showed that the quantities of crops and livestock products consumed by families under both the baseline and the alternative scenarios provided and even exceeded the daily levels of calories, proteins and fat required for an adult. Levels of calcium and vitamin A were deficient in the baseline scenario, but increased to meet the daily requirements for an adult under each of the alternative scenarios. The simulated levels of iron did not change from the baseline to the alternative scenarios; thus, families in Bihinaayili will require food supplements (whether obtained through purchase or farming) to meet the minimum nutritional requirements for iron. The analysis and comparison of alternative irrigated crops and their effects on farm-family nutrition are subjects for proposed future study.

5. Conclusions

In Bihinaayili, ILSSI proposes implementing SSI, using water from water harvesting ponds (dugouts) along the stream networks and one of three alternative water-lifting technologies, to maximize cultivation of high-value vegetable and fodder crops in the dry season. 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

Simulations indicated that there is ample water available for the proposed SSI interventions in the Bihinaayili watershed. Because dugouts were used to collect and store water subsequently used for dry-season irrigation, the proposed SSI interventions affected both the amount and the timing of the stream flows in the Bihinaayili watershed. Simulations indicated that the proposed SSI interventions would reduce average monthly stream flow by 37%, reduce peak flows, and increase low flows. The decrease in average monthly stream flows may have negative impacts on downstream social-ecological systems; however, the decrease in peak flows, increase in low flows, and reduction in sediment influxes may have positive implications for upstream and downstream social and ecological systems. The dugouts used to store irrigation water will be susceptible to siltation, and dredging sediment loads from the dugouts to the fields will be a challenging task.

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizers would increase crop yields substantially. The implementation of multiple-cropping systems also affected simulated crop yields and sediment losses. Proper understanding and use of multiple-cropping combinations could increase crop yields and improve soil health, but some combinations would probably decrease productivity. For the fertilizer application scenarios simulated in this study, multiple cropping of maize or sorghum with pepper or tomato resulted in significant increases in simulated maize and sorghum yields, but decreases in simulated pepper and tomato yields. Multiple cropping of maize or sorghum with fodder significantly increased simulated maize and sorghum yields and did not significantly affect fodder yields. In contrast, multiple cropping of soybean with dry-season crops did not significantly affect simulated yields of soybean or the dry-season crops.

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping systems) on farm-family economics in Bihinaayili village. These simulations also compared the costs and benefits of three alternative water-lifting technologies: pulley-and-bucket irrigation; diesel-pump (both rented and owned) irrigation; and solar-pump irrigation. In all, six scenarios (including the baseline, non-irrigated scenario) were simulated. The scenarios that implemented multiple cropping of soybean (rather than maize) with diesel- and solar-pump-irrigated dry-season crops produced by far the highest net present value, net cash farm income, and ending cash reserves of the scenarios simulated (including the baseline, non-irrigated scenario). In contrast, the scenarios that included multiple cropping of maize with diesel-pump-irrigated dry-season crops and multiple cropping of soybean with pulley-irrigated dry-season crops did not differ greatly from the baseline, non-irrigated scenario.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies in iron persisted under the simulated, improved cropping systems. 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 simulation and field research.

Appendix A1

Crop management schedules and fertilization (type and application rate) for cropping systems simulated with SWAT

Crop management data for the baseline scenario in the Bihinaayili watershed

Crop management data for maize and sorghum during the baseline condition:

Maize Practice	Dates	Amount	Sorghum Practice	Dates	Amount
Tillage	15-May		Tillage	15-May	
Tillage	1-Jun		Tillage	1-Jun	
Tillage	15-Jun		Tillage	15-Jun	
DAP fertilizer application	15-Jun	50kg/ha	DAP fertilizer application	15-Jun	50 kg/ha
Planting	15-Jun		Planting	15-Jun	
1st stage urea fertilizer application	15-Jul	25 kg/ha	1st stage urea fertilizer application	15-Jul	25 kg/ha
2nd stage urea fertilizer application	15-Aug	25 kg/ha	2nd stage urea fertilizer application	15-Aug	25 kg/ha
Harvest	15-Oct		Harvest	23-Oct	

Crop management for the SSI (ex ante) scenario in the Bihinaayili watershed

Crop management for maize/tomato rotation:

Maize practice	**Dates**	Amount	Tomato Practice	**Dates**	Amount
Tillage	15-May		Tillage	20-Nov	
Tillage	1-Jun		Tillage	5-Dec	
Tillage	15-Jun		DAP fertilizer application	5-Dec	50 kg/ha
DAP fertilizer application	15-Jun	50kg/ha	Planting	5-Dec	
Planting	15-Jun		1st stage urea fertilizer application	5-Dec	25 kg/ha
1st stage urea fertilizer application	15-Jun	25 kg/ha	2nd stage urea fertilizer application	4-Jan	25 kg/ha
2nd stage urea fertilizer application	15-Aug	25 kg/ha	Harvest	21-Apr	
Harvest	15-Oct				

Crop management for soybean/tomato rotation:

Soybean practice	**Dates**	Amount	Tomato Practice	**Dates**	Amount
Tillage	15-May		Tillage	20-Nov	
Tillage	1-Jun		Tillage	5-Dec	
Tillage	15-Jun		DAP fertilizer application	5-Dec	50 kg/ha
DAP fertilizer application	15-Jun	50kg/ha	Planting	5-Dec	
Planting	15-Jun		1st urea fertilizer applic.	5-Dec	25 kg/ha
1st urea fertilizer applic.	15-Jun	25 kg/ha	2nd urea fertilizer applic.	4-Jan	25 kg/ha
2nd urea fertilizer applic.	15-Aug	25 kg/ha	Harvest	21-Apr	
Harvest	15-Oct				

Crop management for sorghum/tomato rotation:

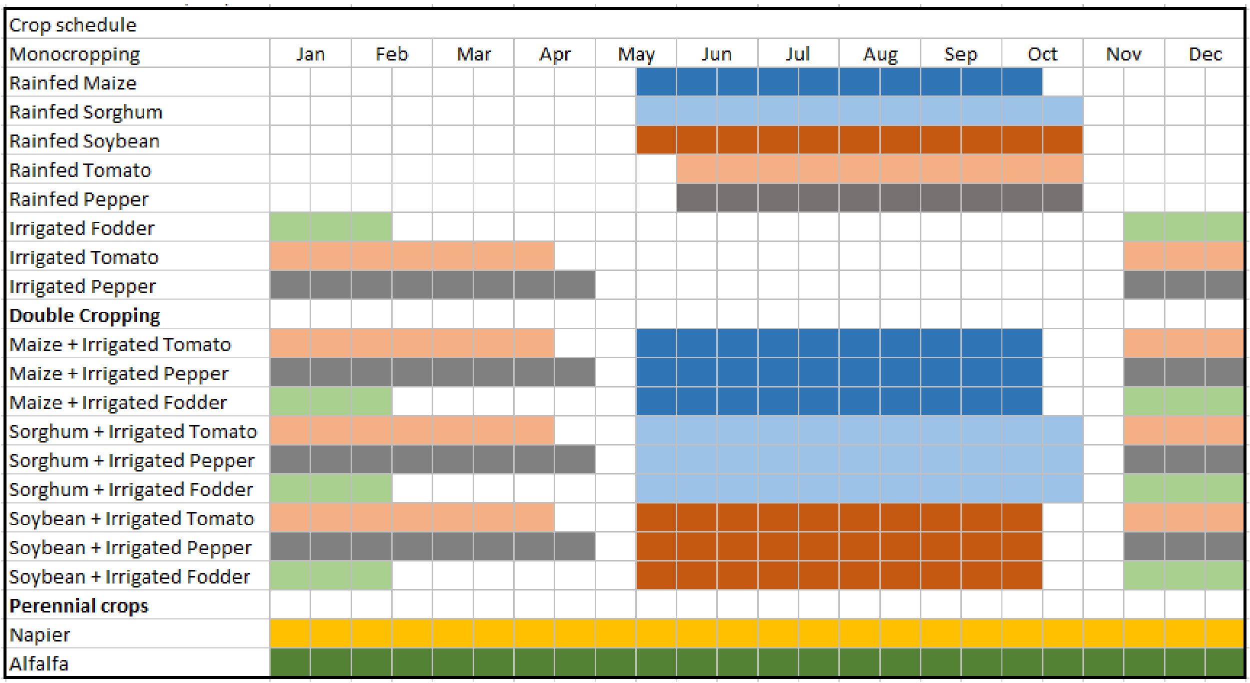
Sorghum practice	**Dates**	Amount	Tomato Practice	**Dates**	Amount
Tillage	15-May		Tillage	10-Nov	
Tillage	1-Jun		Tillage	25-Nov	
Tillage	15-Jun		DAP fertilizer application	25-Nov	50 kg/ha
DAP fertilizer application	15-Jun	50 kg/ha	Planting	25-Nov	
Planting	15-Jun		1st urea fertilizer applic.	25-Nov	25 kg/ha
1st urea fertilizer applic.	15-Jul	25 kg/ha	2nd urea fertilizer applic.	25-Dec	25 kg/ha
2nd urea fertilizer applic.	15-Aug	25 kg/ha	Harvest	11-Apr	
Harvest	23-Oct				

Crop management for Napier grass:

Year	pasture practice	Date	
1	Tillage	17-May	
1	Tillage	1-Jun	
1	DAP fertilizer application	1-Jun	100 kg/ha
1	Planting	1-Jun	
1	harvest	28-Nov	
1	UREA fertilizer application	28-Nov	50 Kg/ha
2	harvest	29-May	
2	UREA fertilizer application	29-May	50 Kg/ha
2	harvest	28-Nov	
2	UREA fertilizer application	29-Nov	50 Kg/ha
3	Harvest	28-May	
3	UREA fertilizer application	29-May	50 Kg/ha
3	harvest and kill	10-May	

Appendix A2

Cropping schedules for the Bihinaayili watershed, as simulated with APEX



Crop schedule												
Monocropping	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfed Maize					⬜🟦	🟦🟦	🟦🟦	🟦🟦	🟦🟦	🟦⬜		
Rainfed Sorghum					⬜▨	▨▨	▨▨	▨▨	▨▨	▨▨		
Rainfed Soybean					⬜🟫	🟫🟫	🟫🟫	🟫🟫	🟫🟫	🟫🟫		
Rainfed Tomato						🟧🟧	🟧🟧	🟧🟧	🟧🟧	🟧🟧		
Rainfed Pepper						⬛⬛	⬛⬛	⬛⬛	⬛⬛	⬛⬛		
Irrigated Fodder	🟩🟩	🟩⬜									⬜🟩	🟩🟩
Irrigated Tomato	🟧🟧	🟧🟧	🟧🟧	🟧⬜							⬜🟧	🟧🟧
Irrigated Pepper	⬛⬛	⬛⬛	⬛⬛	⬛⬛							⬜⬛	⬛⬛
Double Cropping												
Maize + Irrigated Tomato	🟧🟧	🟧🟧	🟧🟧	🟧⬜	⬜🟦	🟦🟦	🟦🟦	🟦🟦	🟦🟦	🟦⬜	⬜🟧	🟧🟧
Maize + Irrigated Pepper	⬛⬛	⬛⬛	⬛⬛	⬛⬛	⬜🟦	🟦🟦	🟦🟦	🟦🟦	🟦🟦	🟦⬜	⬜⬛	⬛⬛
Maize + Irrigated Fodder	🟩🟩	🟩⬜			⬜🟦	🟦🟦	🟦🟦	🟦🟦	🟦🟦	🟦⬜	⬜🟩	🟩🟩
Sorghum + Irrigated Tomato	🟧🟧	🟧🟧	🟧🟧	🟧⬜	⬜▨	▨▨	▨▨	▨▨	▨▨	▨▨	⬜🟧	🟧🟧
Sorghum + Irrigated Pepper	⬛⬛	⬛⬛	⬛⬛	⬛⬛	⬜▨	▨▨	▨▨	▨▨	▨▨	▨▨	⬜⬛	⬛⬛
Sorghum + Irrigated Fodder	🟩🟩	🟩⬜			⬜▨	▨▨	▨▨	▨▨	▨▨	▨▨	⬜🟩	🟩🟩
Soybean + Irrigated Tomato	🟧🟧	🟧🟧	🟧🟧	🟧⬜	⬜🟫	🟫🟫	🟫🟫	🟫🟫	🟫🟫	🟫⬜	⬜🟧	🟧🟧
Soybean + Irrigated Pepper	⬛⬛	⬛⬛	⬛⬛	⬛⬛	⬜🟫	🟫🟫	🟫🟫	🟫🟫	🟫🟫	🟫⬜	⬜⬛	⬛⬛
Soybean + Irrigated Fodder	🟩🟩	🟩⬜			⬜🟫	🟫🟫	🟫🟫	🟫🟫	🟫🟫	🟫⬜	⬜🟩	🟩🟩
Perennial crops												
Napier	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨	🟨🟨
Alfalfa	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩	🟩🟩

Crop management schedules and fertilization (type and application rate) for cropping systems simulated with APEX: a) maize, b) sorghum, c) tomato, pepper and fodder (vetch + oats), d) SRI sorghum, e) alfalfa and f) Napier grass

a). Maize schedule with and without fertilizer

Maize Practice	Dates	Without fertilizer	With fertilizer
Tillage	15-May		
Tillage	1-Jun		
Tillage	15-Jun		
DAP fertilizer application	15-Jun	Don’t apply	50 kg/ha
Planting	15-Jun		
1st stage urea fertilizer application	15-Jul	Don’t apply	25 kg/ha
2nd stage urea fertilizer application	15-Aug	Don’t apply	25 kg/ha
Harvest	15-Oct		

b). Sorghum schedule with and without fertilizer

Sorghum Practice	Dates	Without fertilizer	With fertilizer
Tillage	15-May		
Tillage	1-Jun		
Tillage	15-Jun		
DAP fertilizer application	15-Jun	Don't apply	50 kg/ha
Planting	15-Jun		
1st stage urea fertilizer application	15-Jul	Don't apply	25 kg/ha
2nd stage urea fertilizer application	15-Aug	Don't apply	25 kg/ha
Harvest	23-Oct		

c). Soybean schedule with and without fertilizer

Soybean Practice	Dates	Without fertilizer
Tillage	15-May	
Tillage	1-Jun	
Tillage	15-Jun	
DAP fertilizer application	15-Jun	50 kg/ha
Planting	15-Jun	
1st stage urea fertilizer application	15-Jul	Don't apply
2nd stage urea fertilizer application	15-Aug	Don't apply
Harvest	15-Jun	

d). Tomato, pepper and fodder schedule

Operation	Rainfed Tomato	Irrigated Tomato	Rainfed pepper	Irrigated pepper	Irrigated fodder (Oats/Vetch)
Tillage	1-Jun	10-Nov	1-Jun	23-Nov	30-Nov
Tillage	15-Jun	25-Nov	15-Jun	8-Dec	15-Dec
DAP application (50 kg/ha)	15-Jun	25-Nov	15-Jun	8-Dec	15-Dec
Planting	15-Jun	25-Nov	15-Jun	8-Dec	15-Dec
1st stage urea application (25 kg/ha)	15-Jun	25-Nov	15-Jun	8-Dec	15-Dec
2nd stage urea application (25 kg/ha)	15-Jul	25-Nov	15-Jul	7-Jan	10-Jan
Harvest	31-Oct	11-Apr	2-Nov	26-Apr	13-Feb

e) Alfalfa schedule

Year	Operations	Date	Notes
1st year	Tillage	1/5	
1st year	Tillage	1/20	

1st year	DAP fertilizer application	1/20 (100 kg/ha)	At planting
1st year	Planting	1/20	
1st year	1st Cut	7/19	First cut after 6 months
1st year	Cut	9/17	Harvest every 60 days weeks
1st year	Cut	11/16	Harvest every 60 days weeks
2nd year	Cut	1/15	Harvest
2nd year	DAP fertilizer application	1/20 (100 kg/ha)	Once a year every year (second year)
2nd year	Cut	3/15	Harvest
2nd year	Cut	5/14	Harvest
2nd year	Cut	7/13	Harvest
2nd year	Cut	9/11	Harvest
2nd year	Cut	11/10	Harvest
3rd year	Cut	1/9	Harvest
3rd year	DAP fertilizer application	1/20 (100 kg/ha)	Once a year every year (third year)
3rd year	Cut	3/10	Harvest
		Successive cut every 6 weeks	
4th year	DAP fertilizer application	1/20 (100 kg/ha)	Once a year every year (forth year)
4th year	Cut	3/5	Harvest
		Successive cut every 60 days	
5th year	Harvest	12/25	Harvest
5th year	Kill and replant	12/14 After	Kill and replant

f) Napier grass schedule

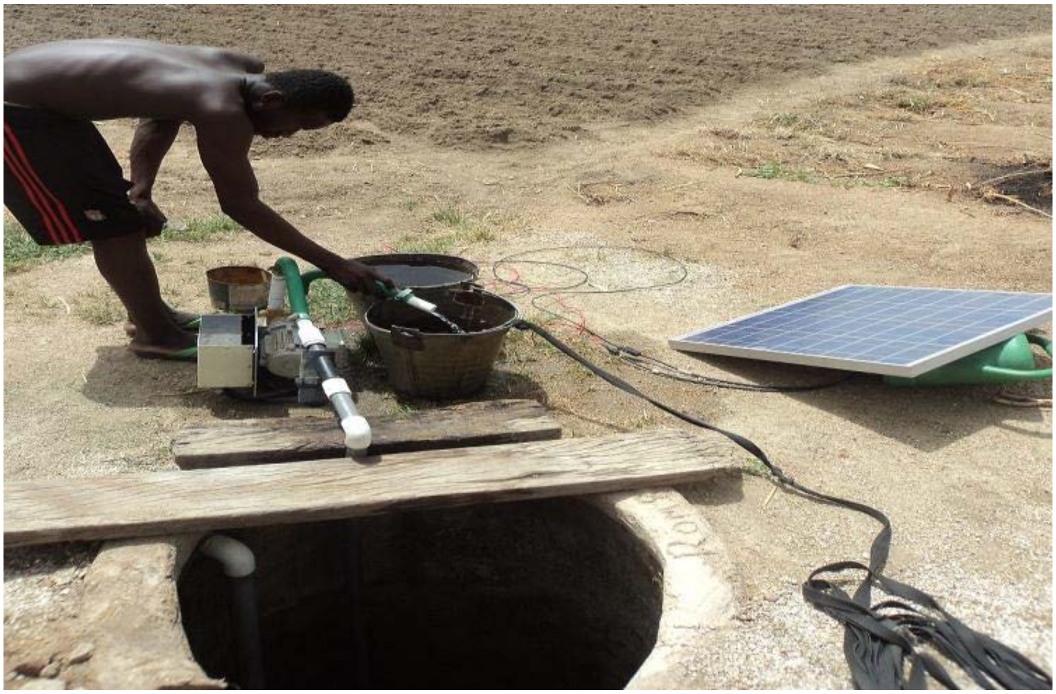
Year	Operations	Date	Notes
1st year	Tillage	1/1	
1st year	Tillage	1/20	
1st year	DAP fertilizer application	1/20 (100 kg/ha)	One time only
1st year	Urea fertilizer application	1/20 (100 kg/ha)	At planting
1st year	Planting	1/20	
1st year	1st Cut	4/20	First cut after 3 months
1st year	Urea fertilizer application	4/21 (100 kg/ha)	After every cut
1st year	Cut	6/19	Harvest every 60 days
1st year	Urea fertilizer application	6/20 (100 kg/ha)	After every cut
1st year	Cut	8/18	Harvest
1st year	Urea fertilizer application	8/19 (100 kg/ha)	After every cut
1st year	Cut	10/17	Harvest
1st year	Urea fertilizer application	10/18 (100 kg/ha)	After every cut
1st year	Cut	12/16	Harvest
1st year	Urea fertilizer application	12/17 (100 kg/ha)	After every cut
2st year	Cut	2/14	Harvest
2st year	Urea fertilizer application	2/15 (100 kg/ha)	After every cut
2st year	Cut	4/14	Harvest
	Successive cut every 60 days and 100 kg/ha urea will be applied next day		
3rd year	Harvest	12/5	Harvest
3rd year	Kill and replant	12/6	Kill and replant

Appendix B

Water-lifting tools

Pulley/Bucket system (Bahir Dar, Ethiopia)

Motor pump drawing water from river (Bochesa, Ethiopia)



Solar pump installed in Ghana. (Source: Bern University of Applied Sciences, 2013)

Solar pump in rice field in Rangpur, Bangladesh. (Source: Imoberdorf, K. MSc thesis, 2012)

Prototype of a small-scale solar pump developed by BUAS (Rangpur, Bangladesh).
(Source: Imoberdorf, K. MSc thesis, 2012)

Service provider transporting solar pump (Source: Bern University of Applied Science, 2013)

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