Ex Ante Analysis of Small-Scale Irrigation Interventions in Zanlerigu

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The authors wish to acknowledge the following agencies and individuals who were instrumental in providing data and expert advice for this report: our partners at the International Water Management Institute; and Cleophilia Roberts and Carlo Azzarri of the International Food Policy Research Institute.

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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 Zanlerigu watershed, in the Nabdam District in the Upper East Region of Ghana. The annual crops yields produced in the area are far below global average yields. Farm-family livelihoods are derived from main crops, such as maize and millet, produced in the rainy season. Vegetables such as tomato and red 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 Zanlerigu, ILSSI proposes implementing SSI, using shallow groundwater 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 and millet), using current (minimal) irrigation; and
ii. multiple cropping of fertilized rainy-season crops (maize and millet), 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 of watershed-scale hydrology indicated that there is large water resources potential in the Zanlerigu watershed. The total annual groundwater recharge was more than 112 mm, and the annual generated surface runoff was more than 73 mm. However, the average annual irrigation water requirement for cultivating dry-season pepper and Napier grass exceeded the average annual shallow groundwater recharge. Implementation of SSI for dry-season pepper and Napier grass production caused a modest reduction in the monthly stream flow. Peak flows and low flows also decreased with implementation of the irrigated pepper/Napier grass scenario.

Since the shallow groundwater recharge was not sufficient to meet the irrigation water requirement, we would recommend combining irrigation from the shallow groundwater aquifer with irrigation from other water sources. For example, water-harvesting ponds (dugouts), used in other watersheds for SSI purposes, could be used to store and capture surface runoff for SSI in the Zanlerigu watershed. We would also recommend selecting water-efficient crops for dry-season cultivation in order to minimize reductions in stream flow. Analyses of potential dugout sites and scale, likely costs and benefits of irrigating from dugouts, and recommendations as specific water-efficient crops for cultivation, were beyond the scope of this study but could be addressed in future research.

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizers would increase crop yields substantially without a considerable impact on the environment. More specifically, the addition of 50 kg/ha of urea and 50 kg/ha or DAP doubled maize and millet yields without significantly affecting runoff or sediment yield. Proper understanding and use of multiple-cropping combinations could also increase crop yields and improve soil health, although some combinations would probably decrease productivity. For the fertilizer application scenarios simulated in this study, multiple cropping of rainy-season maize and millet with dry-season fodder (oats/vetch) increased simulated maize and millet yields substantially by increasing residual nitrogen, and did not adversely affect fodder yields. Multiple cropping of the grain crops with tomato increased simulated maize and millet yields by lesser amounts; however, tomato yields decreased with multiple cropping. Finally, high temperature stress was also a major factor limiting yields of certain crops, such as pepper and oats. The yield of pepper planted as a rain-fed crop in the cooler season was double that of irrigated, dry-season pepper. Planting temperature-sensitive crops in the cooler season would therefore also optimize yields.

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 Zanlerigu 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, five scenarios (including the baseline, non-irrigated scenario) were simulated. The pulley-irrigated, multiple-cropping scenario did not differ greatly from the baseline, non-irrigated scenario. In contrast, the scenarios that implemented multiple cropping of grain crops 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). Given the lower maintenance and environmental costs of solar pumps, simulation results suggest that investments in solar water-lifting technologies will pay dividends in the long run.

The simulated, improved cropping systems resulted in improvements in farm-family nutrition. While levels of fat were deficient and levels of calcium, iron, and vitamin A were merely adequate in the baseline, non-irrigated scenario, in the alternative scenarios, levels of fat and vitamin A exceeded daily requirements (though levels of calcium and iron remained at only adequate levels). We would propose expanding the types of crops irrigated in the dry season to further 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.

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 Zanlerigu watershed, in the Nabdam District in the Upper East 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 Zanlerigu 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.

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 and millet) grown during the main rainy season, using current (minimal) irrigation. The proposed SSI interventions used shallow groundwater to enable multiple cropping of the rainy-season crops (maize and millet) 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.

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. 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 Zanlerigu watershed is located 10°48’08.21” N, 0°43’32.31” W in the Nabdam District in the Upper East Region of Ghana (fig. 1).

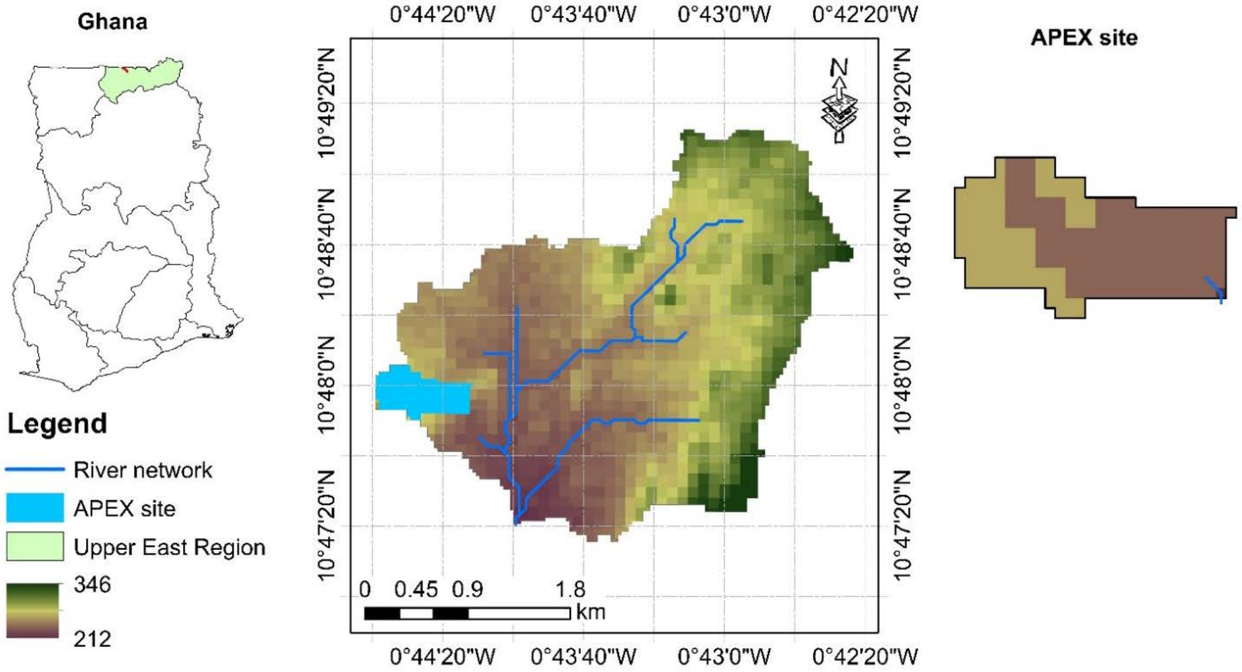


Figure 1. Zanlerigu watershed boundary, main streams and Subarea 21, simulated with APEX.

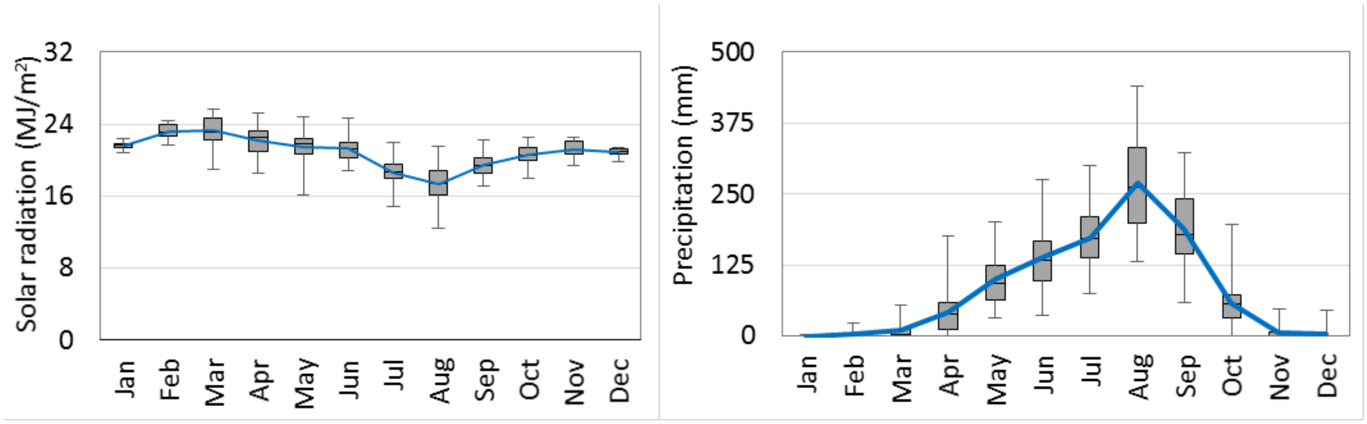
The watershed covers a 838.26-ha area, is characterized as level to undulating, with elevations ranging from 212 meters above mean sea level (mamsl) to 346 mamsl. The average percent slope of the watershed, computed from 30m-resolution Enhanced Shuttle Land Elevation Data, is approximately 7%. Two types of land use were identified in the Zanlerigu watershed: agricultural land (56.28%), and forestland (43.72%) (USGS EarthExplorer). Only one soil type, loamy soil, was identified in the watershed.

Unlike southern Ghana, where year-round rainfall allows for multiple cropping seasons, the Upper East 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 2013, the average annual rainfall was approximately 1,000 mm and the watershed received 75% to 90% 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 Zanlerigu area are sorghum, millet, groundnut, tomato, and chili pepper, with maize and millet being the dominant crops.

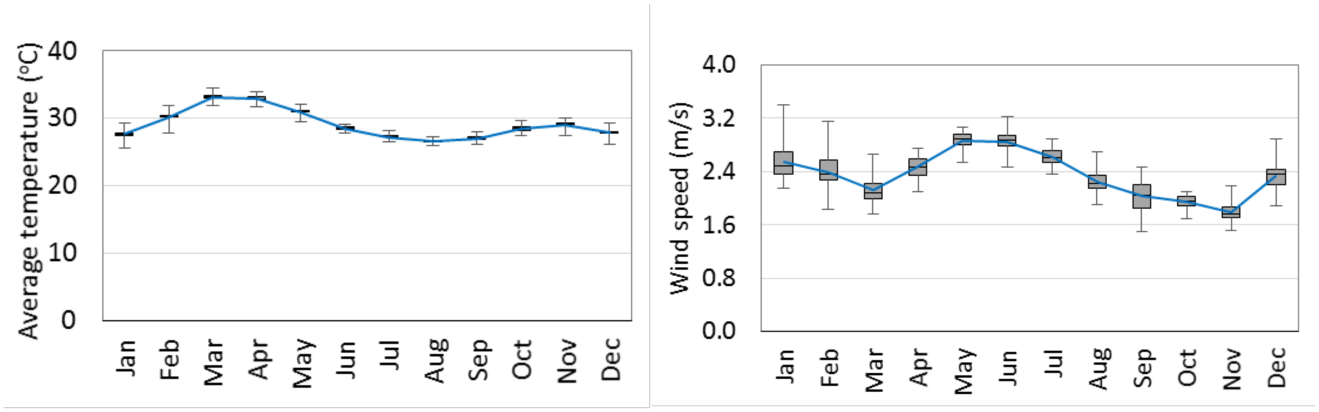
For APEX, a sub-watershed dominated by agricultural land (subarea 21, equivalent to SWAT's subbasin 21) was selected (fig 1). The sub-watershed selected for APEX is located at the outlet of the Zanlerigu watershed (fig. 1), and is approximately 26.46 ha in area, with elevations varying from 225 mamsl to 275 mamsl. The average percent slope of the sub-watershed is approximately 3.5% (USGS EarthExplorer). The soil in this subarea is comprised of 22% clay, 41% sand, and 37% silt, and is classified as loam soil (Be1-1081) by the Food and Agriculture Organization of the United Nations (FAO). For the period from 1980 to 2013, the average annual rainfall was approximately 1,000 mm/year. Farmers in subarea 21 depend mainly on rain-fed agriculture, with a small group of farmers using shallow wells for irrigation. Farmers mainly apply water by watering cans for onion, cabbage, tomato, and pepper. The dominant crops in the subarea are millet and maize. Zuarungu and the nearest village, Pelungu, are the main potential markets.

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 the nearest river gauging station, at Pwalugu. Daily stream flow data for the Pwalugu river gauging station were available from 1951 to 2006; however, complete data were available only for the period from 2003 to 2006.

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 Zanlerigu 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 and millet.

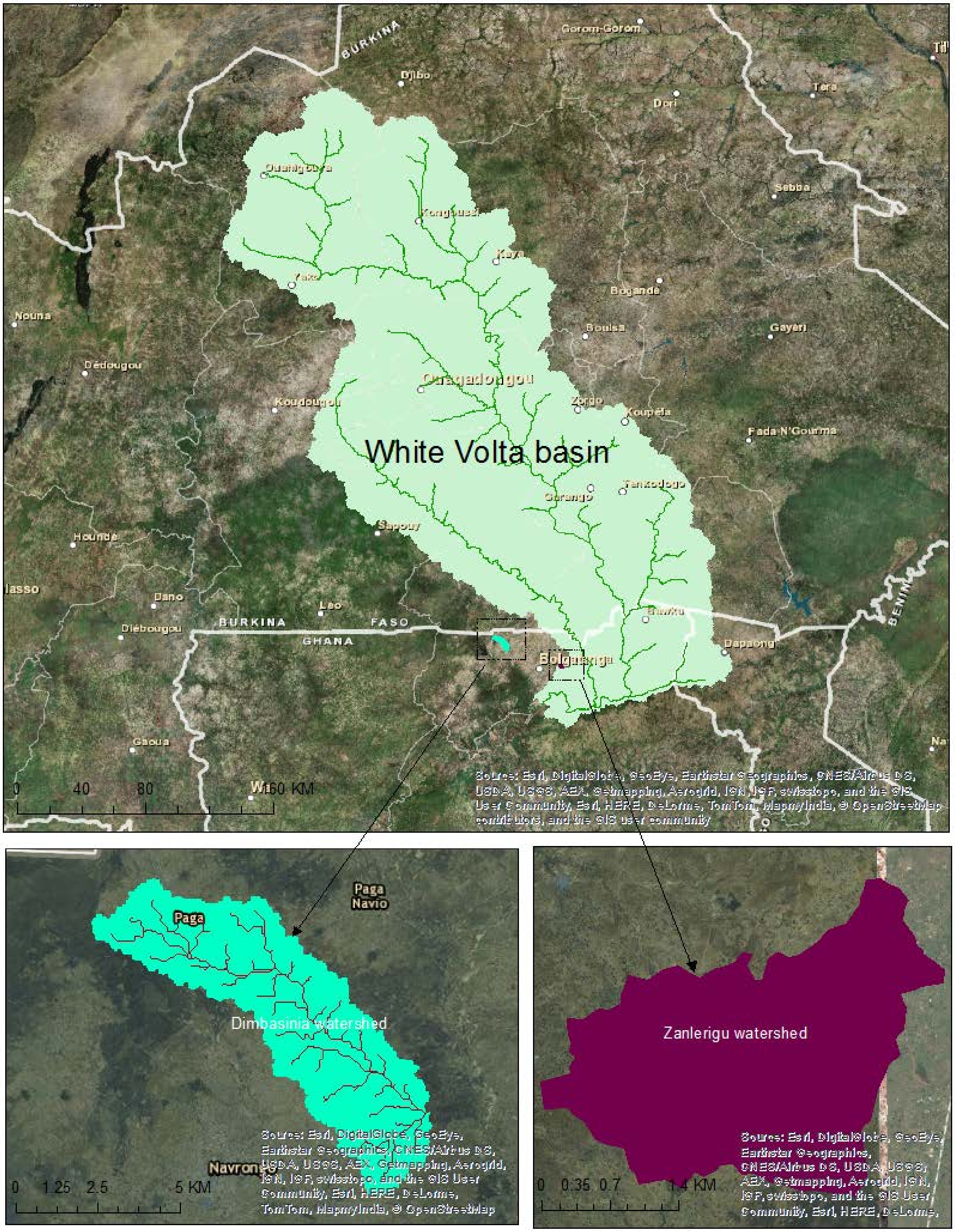
Table 1. SPAM 2005 cycle and FAOSTAT average crop yield (1983 to 2013) (t/ha) for maize and millet.

Dataset	Country	District	Maize (t/ha)	Millet (t/ha)
SPAM (2005)	Ghana	Zanlerigu	1.38	0.98
FAO (1983 to 2013)	Ghana	--	1.55	0.92

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 Zanlerigu watershed. The 838.26-ha watershed was subdivided into 33 subbasins with a mean area of approximately 25 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 Pwalugu river gauging station in the White Volta basin (fig. 3). The White Volta basin has a catchment area of 57,564 km^2. There are 11 land use types in the White Volta basin, of which 42.37% is agricultural land, 36.36% is forested land, and 12.91% is pasture land. The remaining area is comprised of range land, wetland, water, residential, and barren land. There are 35 types of soils in the White Volta basin.



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

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

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Figure 3. The upper panel shows the location of the White Volta basin, which lies over Burkina Faso, Ghana and Togo. The lower panel shows two of the ILSSI study sites: Nimbasinia and Zanlerigu.

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 21, 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 and millet 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), traditional rain-fed crops without fertilizer application and irrigated crops were grown continuously.

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 and millet) in the rainy season with alternative, irrigated and fertilized crops in the dry season; and cultivation of certain perennial fodder crops (e.g., alfalfa and Napier grass). In evaluating the effects of the proposed SSI interventions at the watershed scale, SWAT used shallow groundwater as the source of irrigation water in the Zanlerigu watershed and simulated multiple cropping of rainy-season grain crops with irrigated tomato in the dry season. To provide more detail at the field scale, APEX simulated: multiple cropping 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 the 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 Zanlerigu 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 Zanlerigu community, FARMSIM used household data from a 2014 survey by Africa Rising of nearby community of Shia, located not far from the Zanlerigu community and watershed. The survey indicates that the majority of the area's population derive their livelihoods from subsistence farming, rearing livestock, and hunting, and that the major crops grown, by area, are maize (38 ha) and millet (92 ha), on an estimated total cropland of 230 ha (rain-fed and irrigated). Other major crops, such as rice and groundnuts, are not discussed here, due to the lack of information required for simulation with the APEX model. Vegetables such as tomatoes and red pepper are produced as well on limited land. Pastureland is very limited, and estimated to be about 2 to 3 ha. The main types of livestock produced are cattle, sheep, goats, pigs, 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 four different alternative scenarios in which rainy-season maize and millet were grown as multiple crops with irrigated, dry-season vegetables (tomatoes and red pepper) and fodder (oats and vetch). In contrast to case studies in Bihinaayili and Nimbasinia, APEX yield simulations for Zanlerigu indicated that crop yields were comparable regardless of whether dry-season crops followed rainy-season maize or millet. In fact, APEX yield simulations showed that multiple cropping of dry-season vegetables and fodder with rainy-season grains did not have a significant effect on crop yields and net cash income in the Zanlerigu community; rather, increased fertilizer rates and irrigation in the alternative scenarios drove increases in yields of maize, millet, vegetables, and fodder.

The FARMSIM simulations also considered three different water-lifting technologies to collect irrigation water from shallow wells: 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 158 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 four alternative scenarios.

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. Land allocated to tomatoes and red pepper doubled in alternative scenario 1, and increased seven-fold in alternative scenarios 2, 3, and 4 (in each case, as compared to the baseline scenario). Land allocated fodder doubled in alternative scenario 1, and increased five-fold in alternative scenarios 2, 3, and 4 (in each case, as compared to the baseline scenario).

In each of the alternative scenarios, the dry-season vegetable and fodder crops were irrigated as required to prevent water stress, and maize and millet 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).

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 five scenarios—the baseline scenario and four 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 five 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 five 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 0.77 and 25.5%, respectively. According to Moriasi et al. (2007), the model performance is satisfactory based on the NSE and PBIAS values, respectively. Figure 4 suggests that the model replicated observed stream flow values reasonably well.

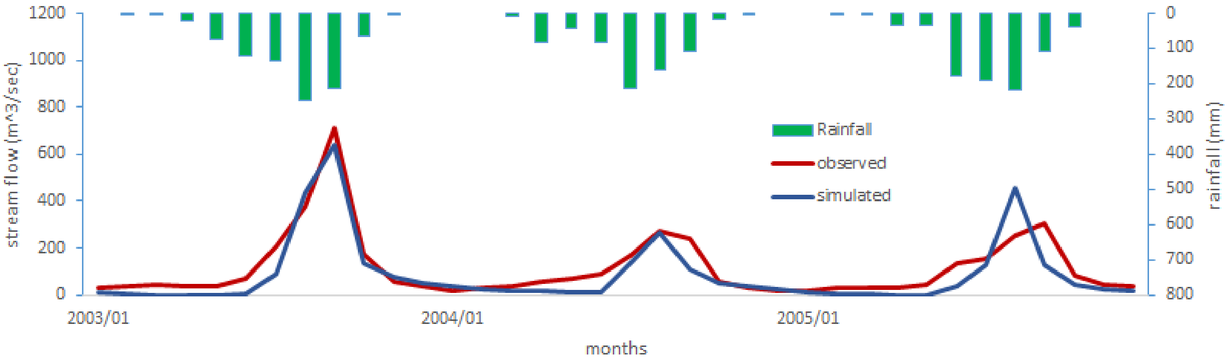


Figure 4. Hydrograph for observed vs simulated monthly stream flow for the White Volta basin at the Pwalugu river gauging station. Complete observed stream flow data was available only for the period from 2003 to 2005. The average monthly rainfall for the White Volta basin is presented in the upper panel in reverse axis.

The calibrated model parameters are presented in Table 2.

Table 2. Calibrated SWAT parameters for the White Volta basin.

Parameter name	Fitted value
r__CN2.mgt	-0.207
v__ALPHA_BF.gw	0.719
v__GW_DELAY.gw	245.3
v__GWQMN.gw	831.6
v__GW_REVAP.gw	0.0154
v__ESCO.hru	0.7639
r__SOL_AWC(1).sol	0.1035

[*] 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 0.94 and R-square value of 0.91. 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 21) rather than the unique features of each of the HRUs within a subarea.

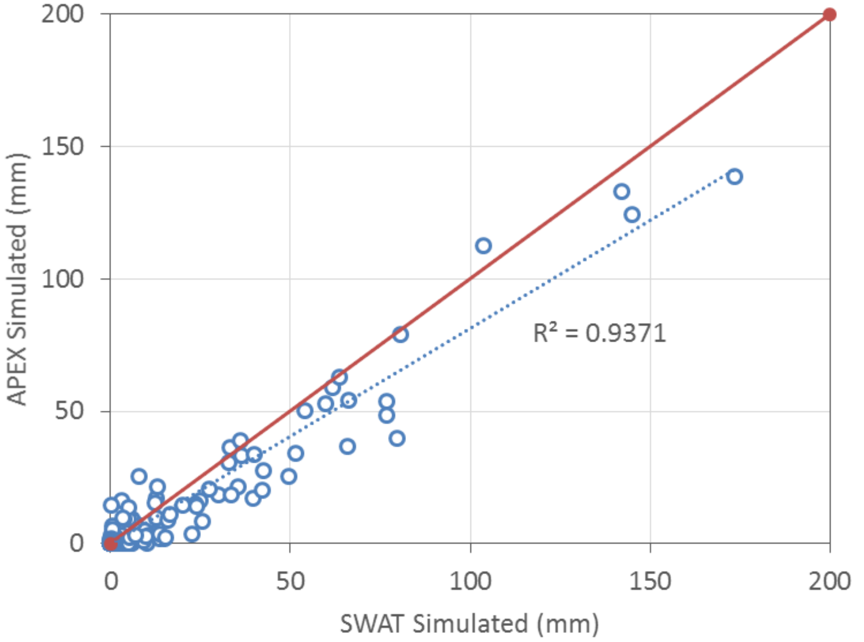


Figure 5: Scatter plot of monthly SWAT and APEX simulated flow for Zanlerigu watershed (1983-2013)

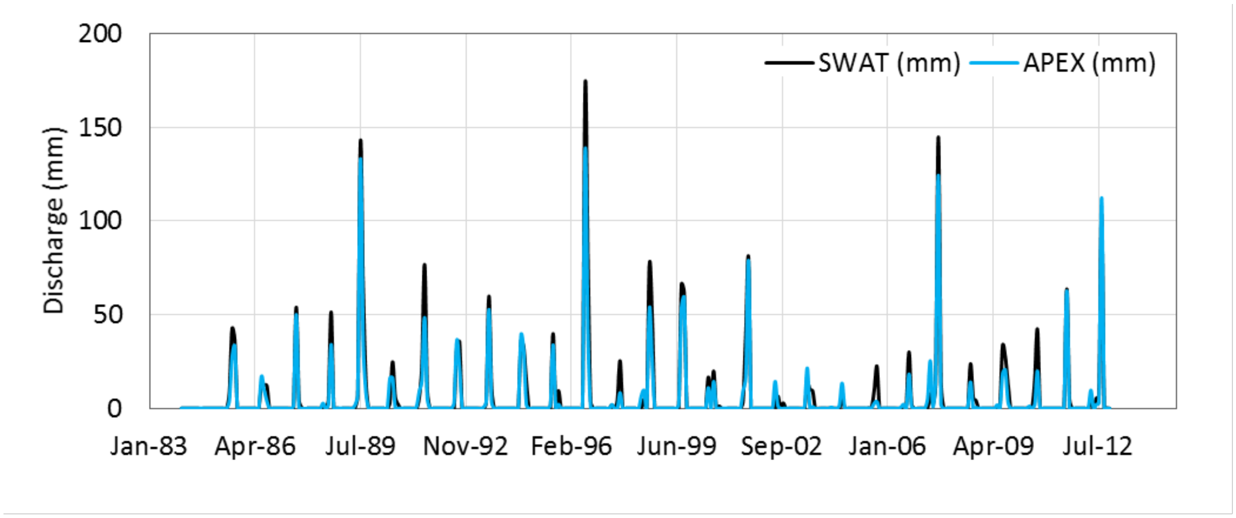


Figure 6. Monthly average SWAT-simulated and APEX-simulated flow for Zanlerigu watershed (1983 – 2013).

The general water balance components of the watershed show evaporation and surface runoff are the dominant processes, contributing 68% and 18%, respectively.

4.1.3 <u>Base period crop yield simulation</u>. APEX reasonably captured the observed yields of maize and millet for the year 2005, with an 8.0% and 11.3% 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 1.0 and 14.5% yield difference for the study period with a RMSE of 0.61 t/ha and 0.39 t/ha for maize and millet, respectively.

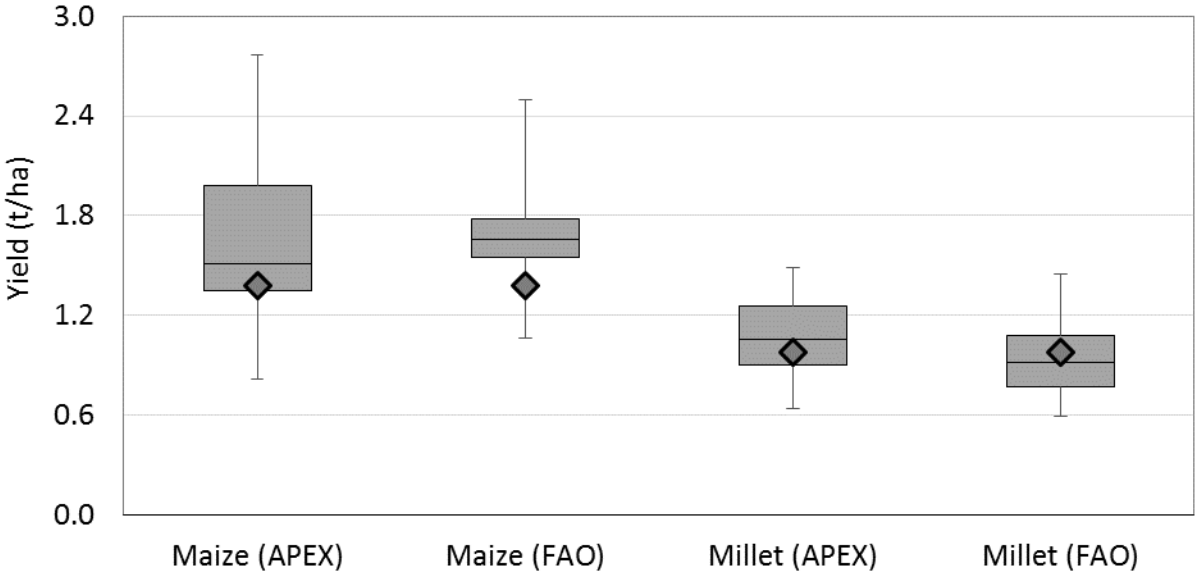


Figure 7: Comparison of APEX vs. FAOSTAT maize and millet yields from 1983 to 2013, with SPAM crop yield for year 2005 represented by a diamond.

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%: millet during the rainy season; and tomato during the dry season;
2) on the remaining portion of the agricultural land where the slope is less than 8%: maize during the rainy season; 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 326.97 ha, or 69.3% of the 471.77 ha of agricultural land in the watershed. Tomato was cultivated on 273.6 ha, and Napier grass on 53.37 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 indicate that groundwater from shallow wells is used extensively for SSI during the dry season. The total number of shallow wells varies from season to season, but on average, each farmer owns three wells. Therefore, this study uses shallow groundwater as a source of irrigation water during the dry season. The shallow groundwater is replenished by groundwater recharge.

4.2.1 Water resources potential. The spatial distributions of the annual groundwater and surface water resources in the Zanlerigu watershed are presented in figure 8. The simulated average annual groundwater recharge varied from 122 mm to 145 mm, and was higher in the mid-land and western side of the watershed. Average annual groundwater recharge fell within the range of 135 mm to 145 mm in 27% of the watershed area, and 125 mm to 135 mm in 46% of the watershed area (fig. 8). The simulated annual generated surface runoff varied from 73 mm to 79 mm, and fell within the range of 77 mm to 79 mm in 69% of the watershed area (fig. 8). For the Zanlerigu watershed, with a catchment area of 838.26 ha, the average annual volumetric groundwater recharge and surface runoff were over 1.1 million m^3 and 0.65 million m^3, respectively.

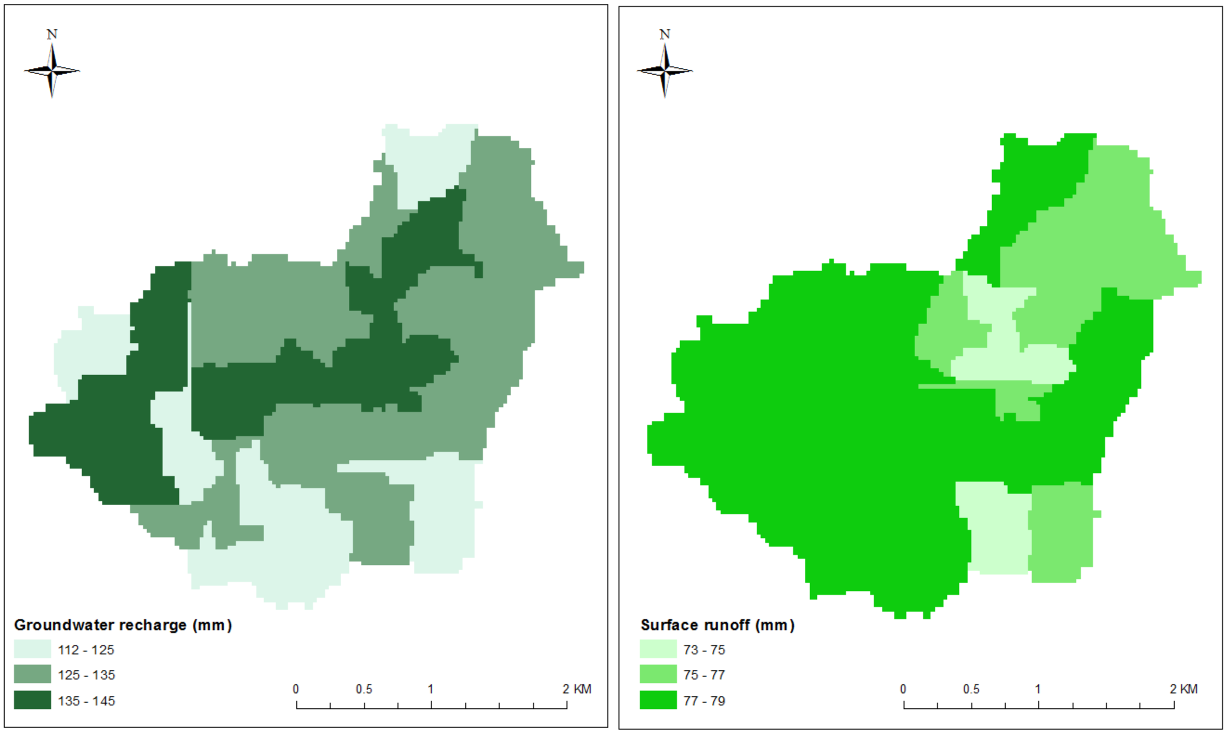


Figure 8. Water resources potential in the Zanlerigu watershed: a) average annual groundwater recharge; and b) average annual surface runoff.

4.2.2 <u>Watershed water balance impacts of the SSI (ex-ante) scenario</u>. The average annual rainfall in the Zanlerigu watershed for the period of 1980 to 2010 was 970.7 mm. About 17% of annual rainfall was turned into stream flow, and 79% evaporated back into the atmosphere. Base flow contributed 54% of stream flow, and surface runoff contributed 46% (fig. 9).

Implementation of the ex-ante scenario using irrigation from shallow groundwater aquifers had a modest effect on overall water balance dynamics. With implementation of irrigation, the base flow contribution to stream flow decreased to 46%, since irrigation water was withdrawn from the shallow groundwater aquifer. Because irrigation led to an increase in soil moisture, which in turn generated increased surface runoff, the surface runoff contribution to total flow increased to 54%. Evaporation increased with irrigation, because of additional evaporation from irrigated fields during the dry season; however, percolation to the soil and deep recharge did not change with irrigation (fig. 9).

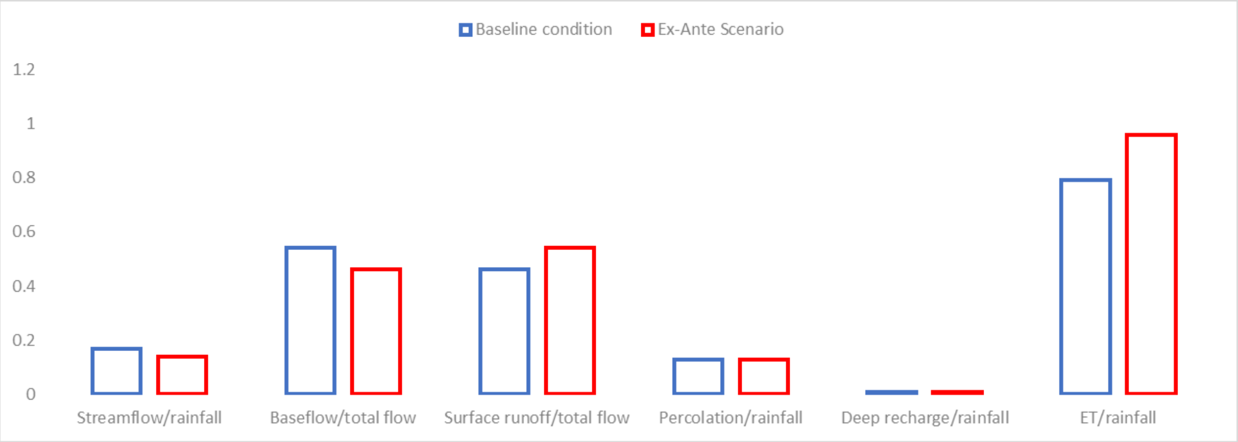


Figure 9. Water balance partitioning for the Zanlerigu watershed in the baseline scenario and ex ante (SSI) scenario.

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 water available in that particular subbasin.

On irrigated fields, the spatio-temporal annual irrigation amount varied from 25 mm to 610 mm, depending on the location of the field within the watershed and the climatic year (fig. 10). In the ex ante (SSI) scenario, the average annual volume of water withdrawn for irrigation in the subbasins ranged from 706 m^3 to 116,655 m^3 (fig. 10). The total annual volume of irrigation water withdrawn was 1,470,127 m^3.

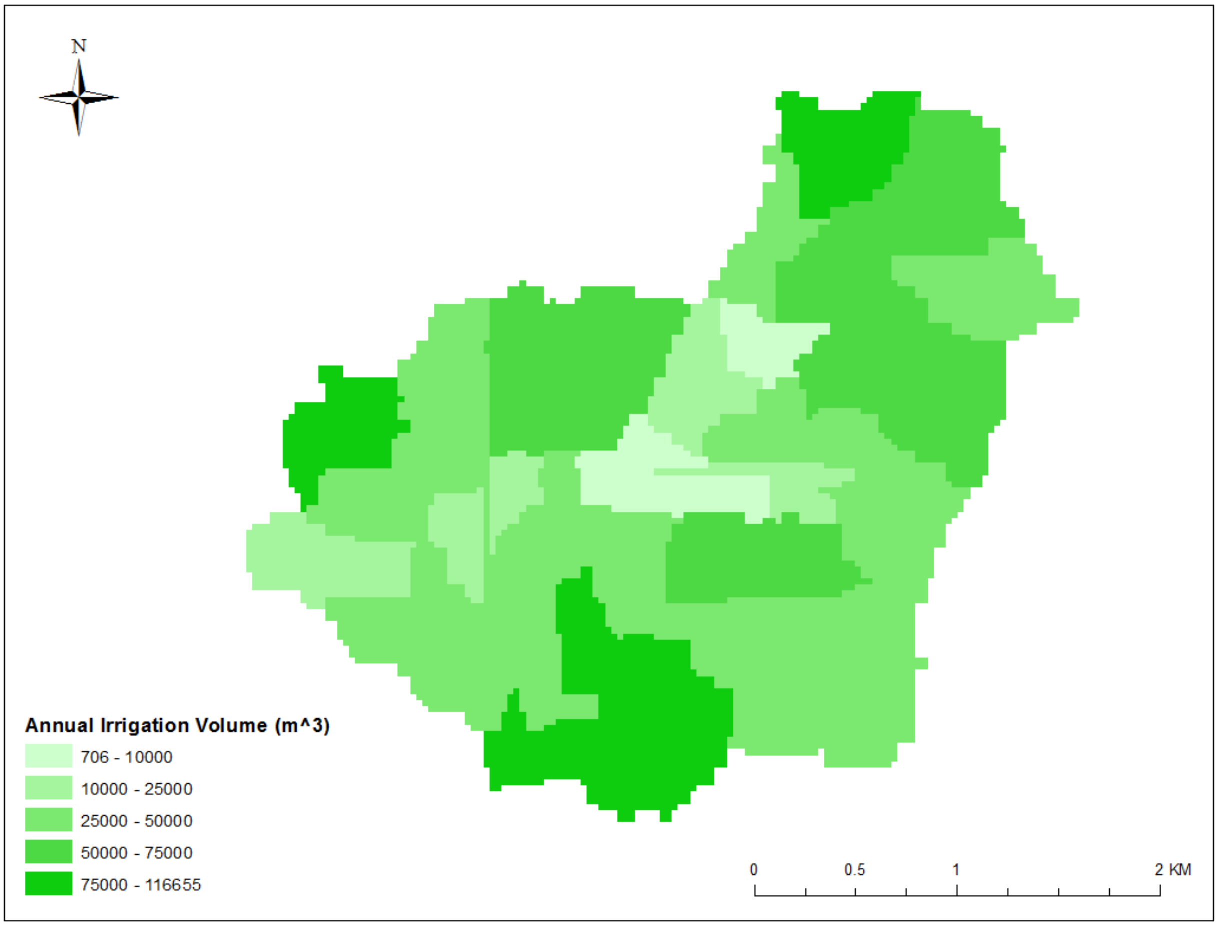


Figure 10. Average annual irrigation volumes (in m^3) for dry-season tomato and Napier grass crops and rainy-season main crop.

4.2.4 Availability of shallow ground water for irrigation. For SWAT simulations, irrigation water was derived from shallow groundwater. Therefore, it was necessary to determine whether shallow groundwater recharge could support the irrigation water requirements for cultivating irrigated, dry season tomato and Napier grass. The simulated average annual shallow groundwater recharge in the Zanlerigu watershed varied from 107 mm to 138 mm (fig. 11a), and the average area-weighted shallow groundwater recharge was 124.46 mm. On the other hand, the average annual irrigation water requirement varied from 5 mm to 405 mm (fig. 11b), and the average area-weighted irrigation over the Zanlerigu watershed was 177.65 mm. In 69.9% of the watershed, the shallow groundwater recharge was less than the irrigation water requirement. This suggests that the annual shallow groundwater recharge cannot support the irrigation water requirements for producing dry-season tomato and Napier grass without affecting long-term groundwater storage.

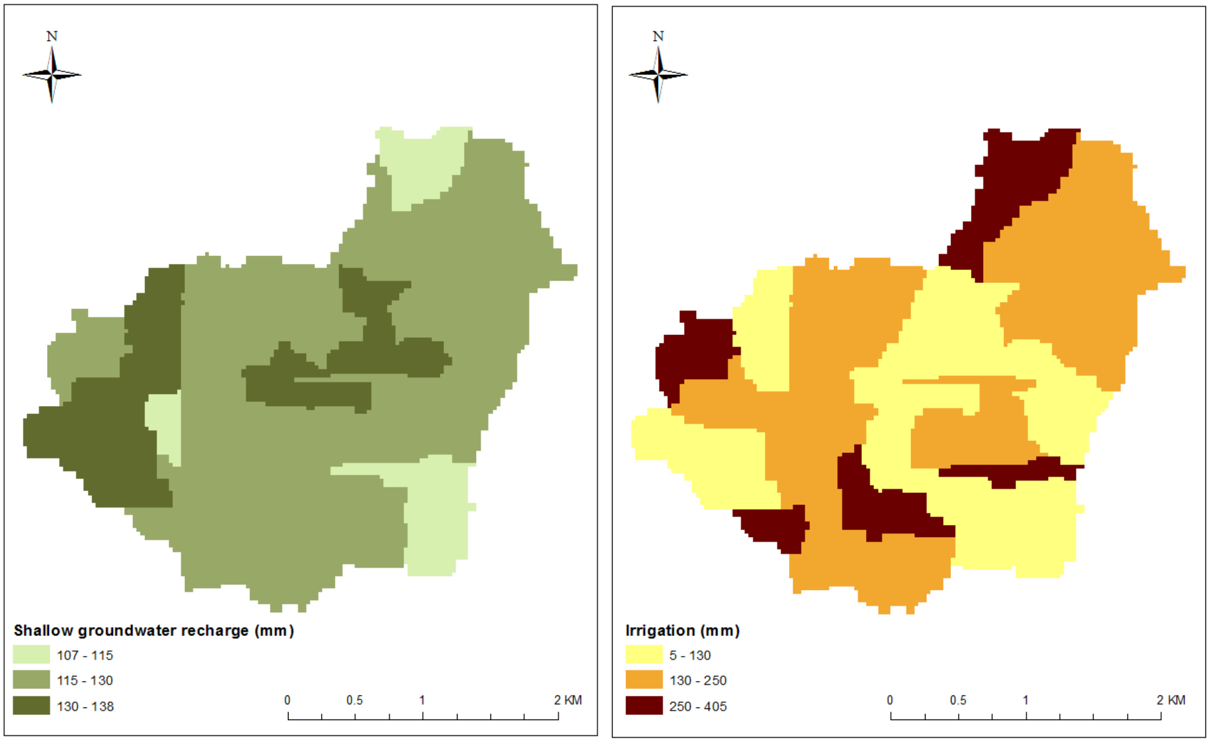


Figure 11. a) Average annual shallow groundwater recharge under baseline conditions, and b) average annual irrigation for cultivating tomato and Napier grass during the dry season.

4.2.5 Changes in stream flows. Implementation of the proposed SSI interventions resulted in a modest reduction to the average stream flow at the outlet of the Zanlerigu watershed. In the baseline scenario, the average monthly stream flow from 1983 to 2010 was 0.046 m^3/sec. Implementation of the proposed SSI interventions during this time period reduced the average monthly stream flow by 15.64% to 0.039 m^3/sec. There was an appreciable difference in the stream flow hydrographs of the baseline and ex ante (SSI) scenarios (fig. 12).

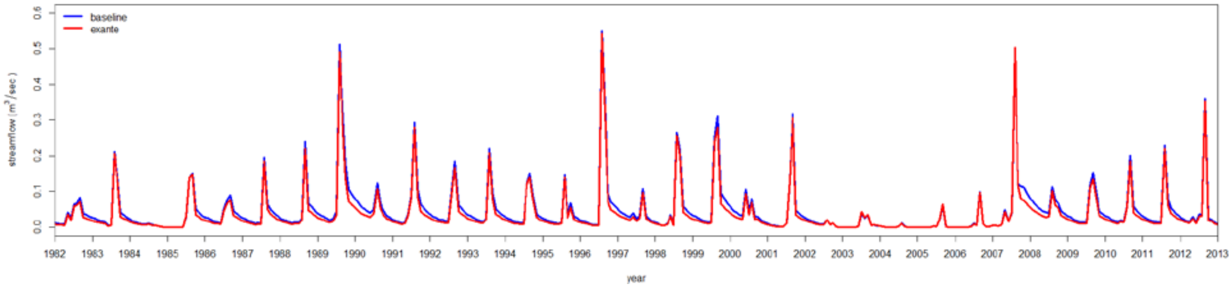


Figure 12. Stream flow at the outlet of the Zanlerigu watershed for the baseline and ex ante (SSI) scenarios.

The flow duration curve indicates that there was consistent reduction of stream flows, including both high and low flows, with the implementation of irrigation from the shallow groundwater aquifer (fig.

13). For example, at 10% probability of exceedance, there was a 19% reduction in stream flow, and at 80% probability of exceedance, there was a 21.5% reduction in stream flow.

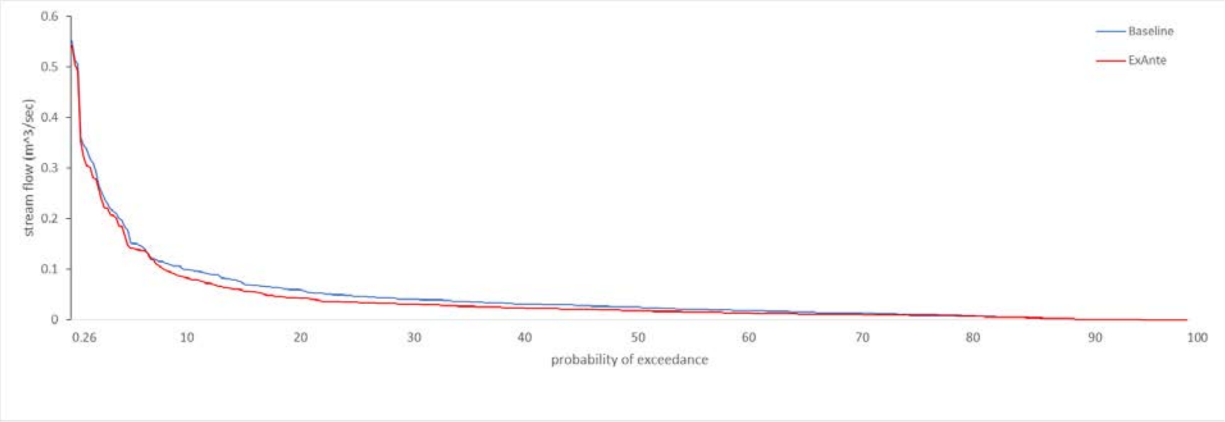


Figure 13. Flow duration curve for the monthly stream flow at the outlet of the Zanlerigu watershed in the baseline scenario and SSI (ex ante) scenario.

4.3 Alternate scenarios simulated with APEX. The analyses that follow reference APEX baseline and alternative scenarios 1-5, summarized below with more detail given in Appendix A2. The baseline and five alternative scenarios simulated by APEX are specifically defined as follows:

Baseline: Maize and millet 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 rainy-season, unfertilized maize 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 rainy-season, unfertilized millet with irrigated crops in the dry season (millet + tomato, millet + pepper, millet + fodder).

Alternative scenario 4: multiple cropping of rainy-season, fertilized millet (using 50 kg/ha of urea, in split applications, and 50 kg/ha DAP) with irrigated crops in the dry season (fertilized millet + tomato, fertilized millet + pepper, fertilized millet + fodder).

Alternative scenario 5: 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 14 indicates the yields of rain-fed maize simulated in a multiple-cropping system with pepper, fodder, and tomato, as compared with continuously-cropped maize. The secondary y-axis in figure 14 indicates the number of nitrogen, water, and temperature stress days over the growing season. Maize yield was limited by nitrogen fertility. Continuously-cropped maize was stressed for nitrogen an average of 59 days per year. Multiple cropping of maize with irrigated fodder and tomato (as opposed to continuous cropping of maize) reduced the nitrogen stress days for the maize crop to 43 and 56 days per year, respectively; consequently, maize yields increased by 99% and 12% when planted with fodder, and tomato, respectively. Multiple cropping of maize with pepper did not change maize yield significantly.

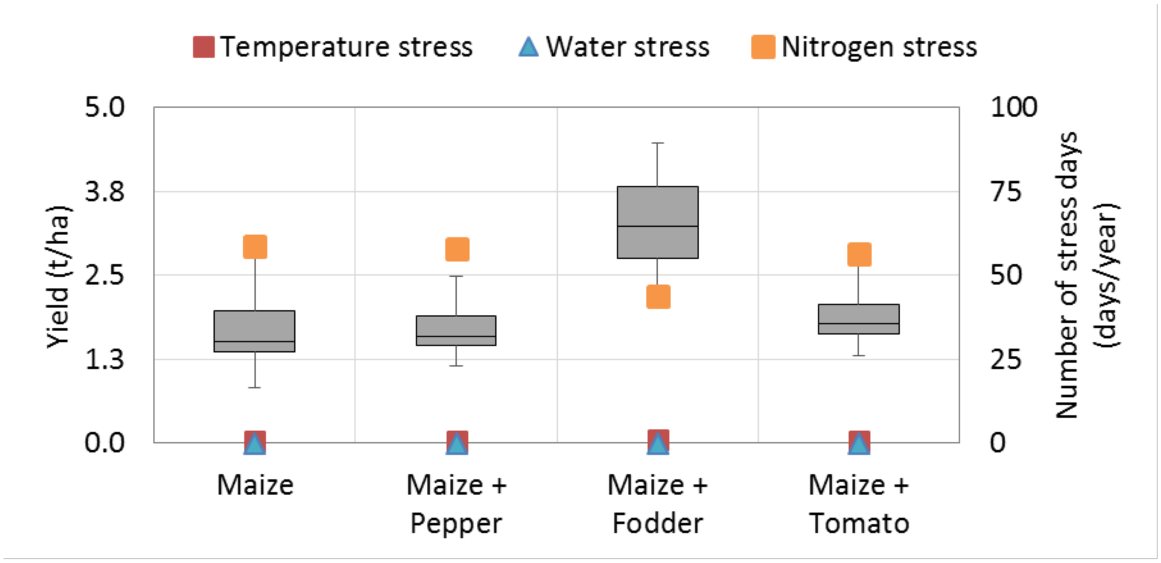


Figure 14. Maize yields when continuously cropped and when grown as a multiple crop with pepper, fodder, and tomato (from 1983 to 2013). In this figure and all of the figures included in Section 4.3, the rectangle box represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

Alternative scenario 2. In alternative scenario 2, we simulated fertilized, rain-fed maize grown in a multiple-cropping system with irrigated dry-season crops of pepper, fodder, and tomato, as compared with continuously-cropped fertilized and unfertilized maize. The results of the simulation are depicted in figure 15. Addition of the fertilizer reduced the number of nitrogen stress days by 26% and consequently increased the yield of continuously-cropped maize by approximately 106% (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 to 41, 21, and 40, respectively. Consequently, multiple cropping of fertilized maize with fodder and tomato increased maize yields by 49% and 9.5%, respectively, compared to the continuously cropped, fertilized maize yield. Multiple cropping of fertilized maize with pepper did not increase maize yield at a p-value of 0.05 (fig. 15).

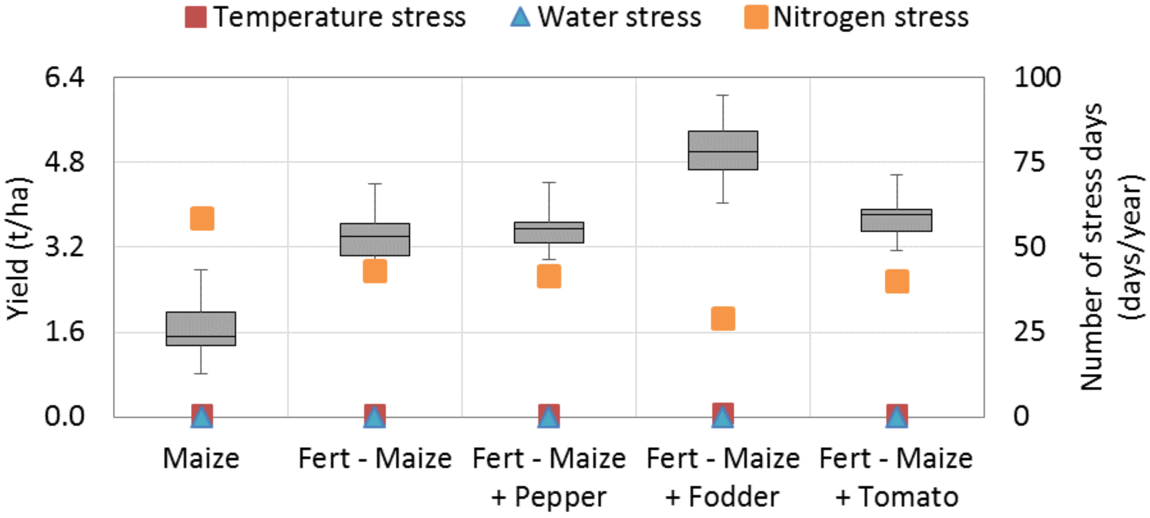


Figure 15. Continuously-cropped, unfertilized maize yield, compared with yields of continuously-cropped, fertilized maize, and fertilized maize grown in a multiple-cropping system.

Alternative scenario 3. Figure 16 indicates the yields of rain-fed millet grown in a multiple-cropping system with irrigated, dry-season pepper, fodder, and tomato, as compared to continuously-planted, rain-fed millet. Continuously-cropped millet was stressed for nitrogen for approximately 63 days per year. Multiple cropping of millet with pepper, fodder, and tomato (as opposed to continuous cropping of millet) reduced the number of nitrogen-stressed days to 59, 42, and 57, respectively; consequently, millet yield increased by 86% and 18% when planted with fodder, and tomato, respectively. Multiple cropping of millet with pepper did not increase the millet yield significantly.

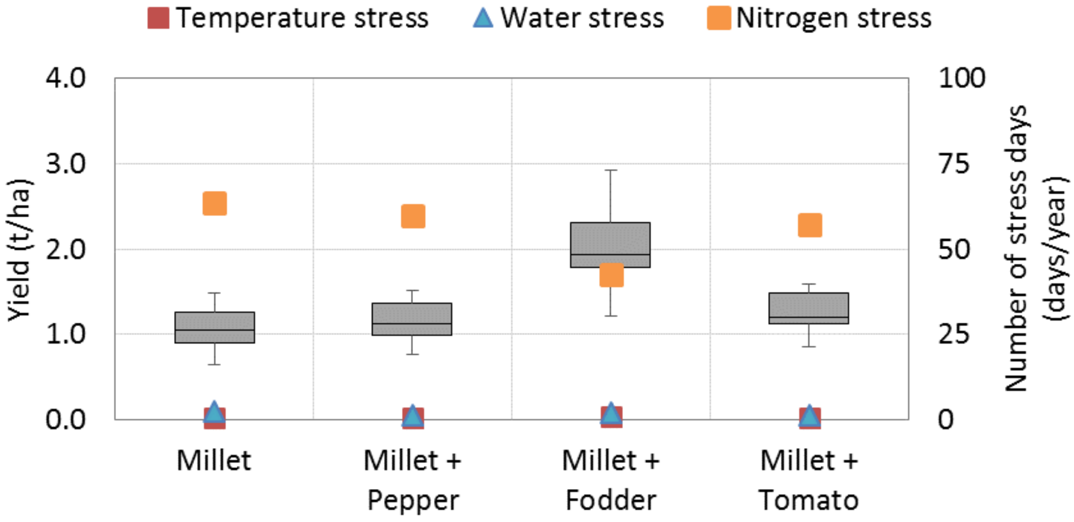


Figure 16. Millet yields when continuously cropped and when grown as a multiple crop with pepper, fodder, and tomato (from 1983 to 2013).

Alternative scenario 4. Figure 17 depicts the simulated results of fertilized, rain-fed millet grown in a multiple-cropping system with irrigated dry-season pepper, fodder, and tomato, as compared to continuously-cropped unfertilized and fertilized millet. Addition of the fertilizer reduced nitrogen stress on the millet crop by 40%, and consequently increased the yield of continuously-cropped millet by 111%. Multiple cropping of fertilized millet with pepper, fodder, and tomato further reduced the nitrogen stress on the millet crop by 6%, 36%, and 11%%, respectively; consequently, yields of millet planted after pepper, fodder, and tomato increased by 7%, 40%, and 12%, respectively (as compared to the continuously-cropped, fertilized millet yield) (fig. 17).

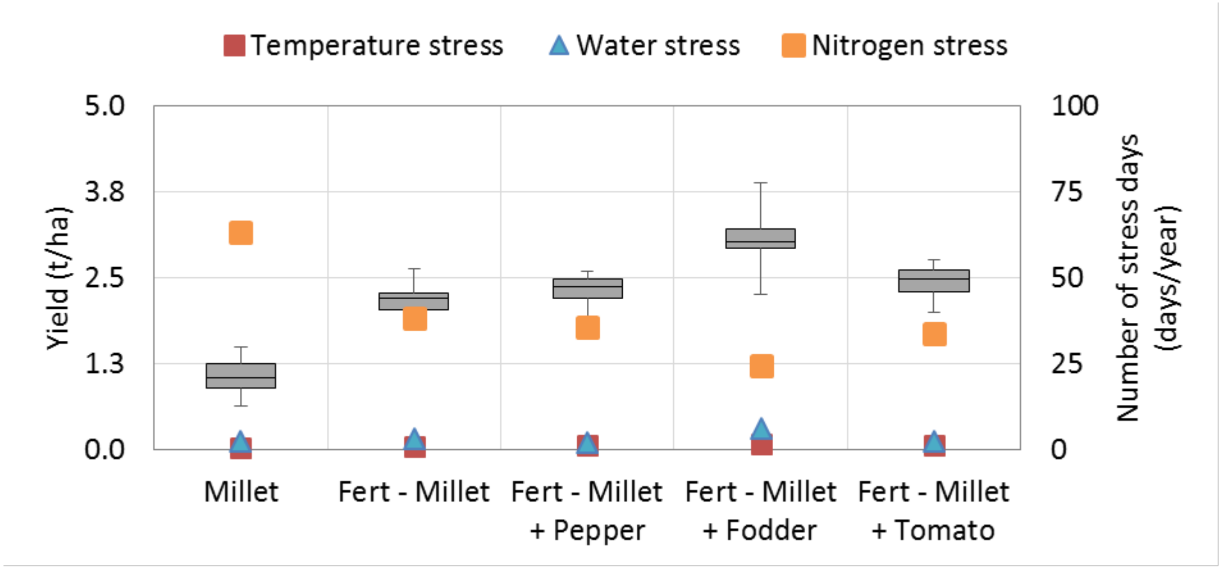


Figure 17. Continuously cropped, unfertilized millet yield, compared with yields of continuously cropped, fertilized millet, and fertilized millet grown in a multiple-cropping system.

The simulated yields of dry-season, irrigated, alternative crops, when planted continuously both as dry-season crops and as rain-fed crops, and as multiple crops with rain-fed maize and millet, are shown in figures 18, 19 and 20. Dry-season crops were irrigated automatically to bring the soil moisture to the filled capacity, and therefore the dry-season crops did not go under water stress. Continuously-planted, dry-season pepper was only under temperature stress for an average of 13 days. Pepper planted as a rain-fed crop reduced the temperature stress days to zero and increased the crop yield by 100%; however, the crop still remained under nitrogen stress for 35 days during the growing season. Multiple cropping of dry-season pepper with rain-fed maize and millet did not significantly affect pepper yields as compared to continuously-cropped, dry-season pepper (fig. 18).

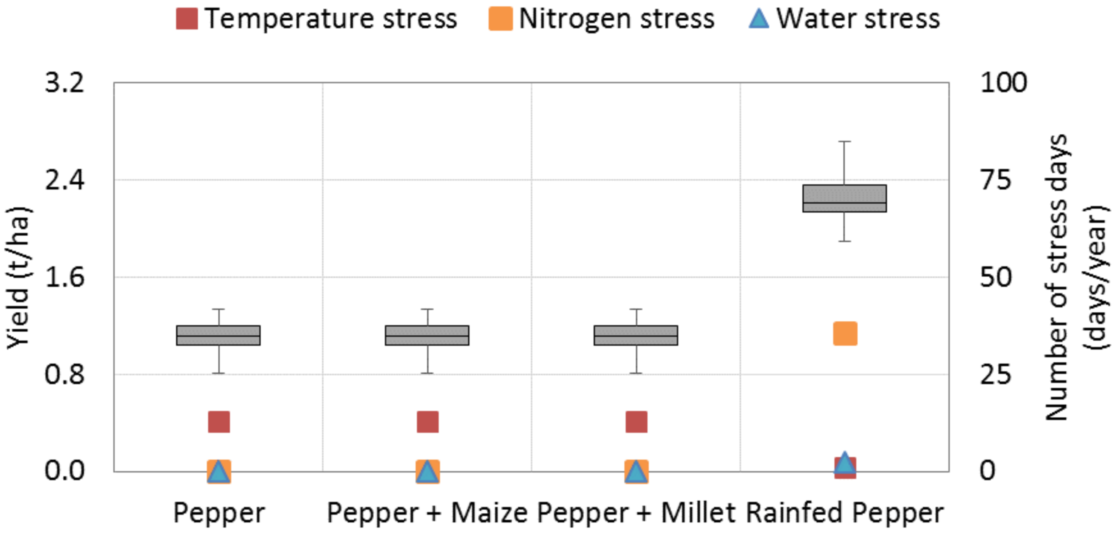


Figure 18. Pepper yield when continuously cropped (as both a dry-season and rain-fed crop), and when grown as a multiple crop with maize and millet (1983 to 2013)

Figure 19 shows simulated fodder yields, when simulated as a continuous crop and as a multiple crop with maize and millet. Temperature was the major factor affecting fodder yield. The oats portion of the oats/vetch fodder mix was under temperature stress for approximately 45 days per year. Multiple cropping of fodder with maize and millet did not have a significant effect on fodder yields (fig. 19).

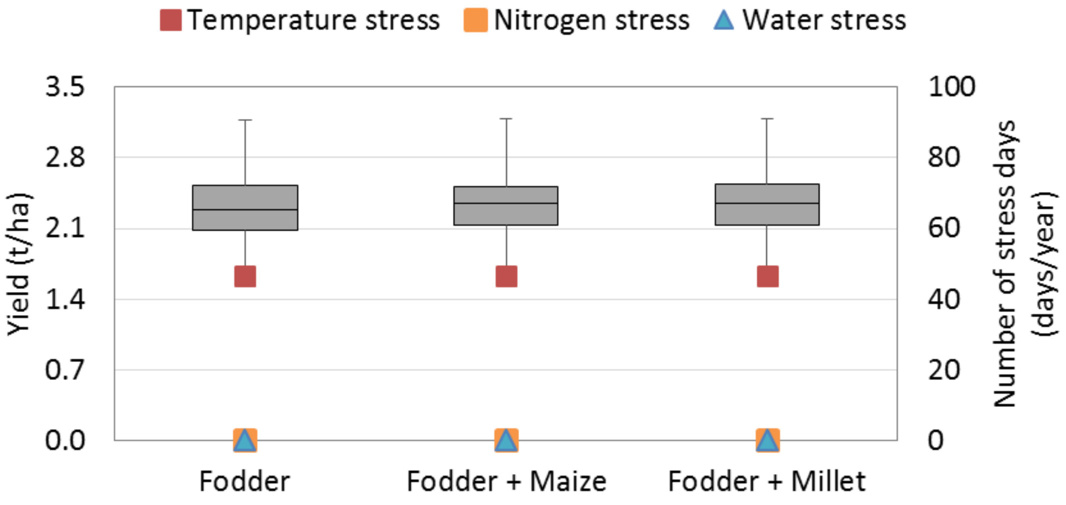


Figure 19. Fodder yield when continuously cropped, and when grown as a multiple crop with maize and millet (1983-2013)

Figure 20 shows simulated yields of tomato when grown as a continuous, irrigated dry-season crop and as a multiple crop with rain-fed maize and millet. Continuously-cropped tomato was under nitrogen stress for an average of 43 days per year. When tomato was simulated as a multiple crop with maize and millet, nitrogen stress days for the tomato crop increased by 26.2% and 26.6%, respectively, and tomato yields declined by 29% in both cases.

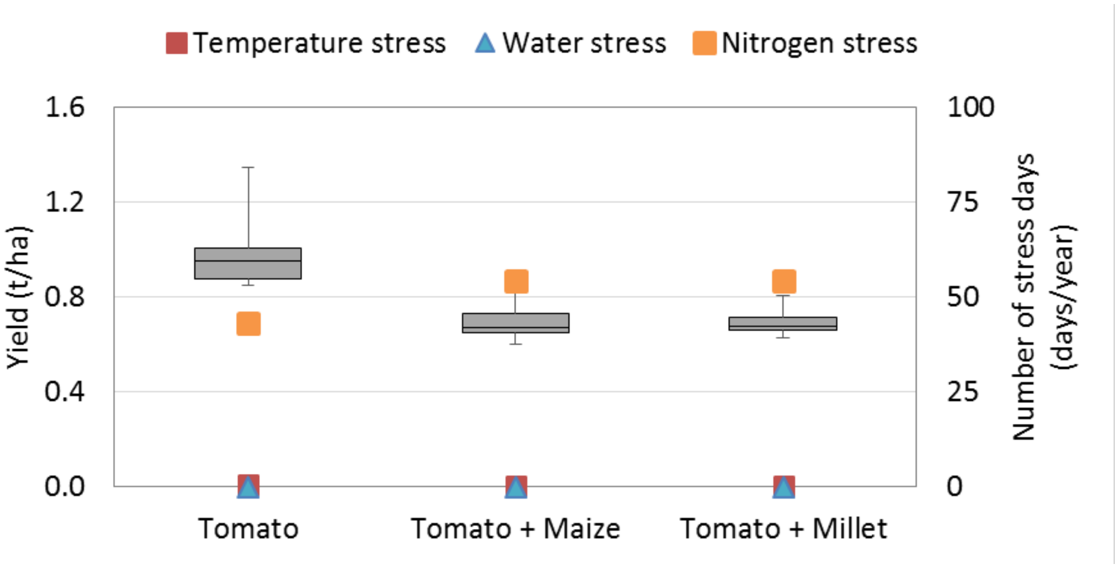


Figure 20. Tomato yield when continuously cropped, and when grown as a multiple crop with maize and millet (1983-2013)

Alternative scenario 5. In alternative scenario 5, 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, nitrogen, and water stress. On average, Napier was stressed for 13, 64, and 114 days per year for high temperature, nitrogen, and water, respectively. Alfalfa was stressed only for temperature, for an average of 142 days per year. Simulated alfalfa yield was comparable to the experimental yield conducted at the University of Cape Coast Research Farm (Bonsu and O 1997).

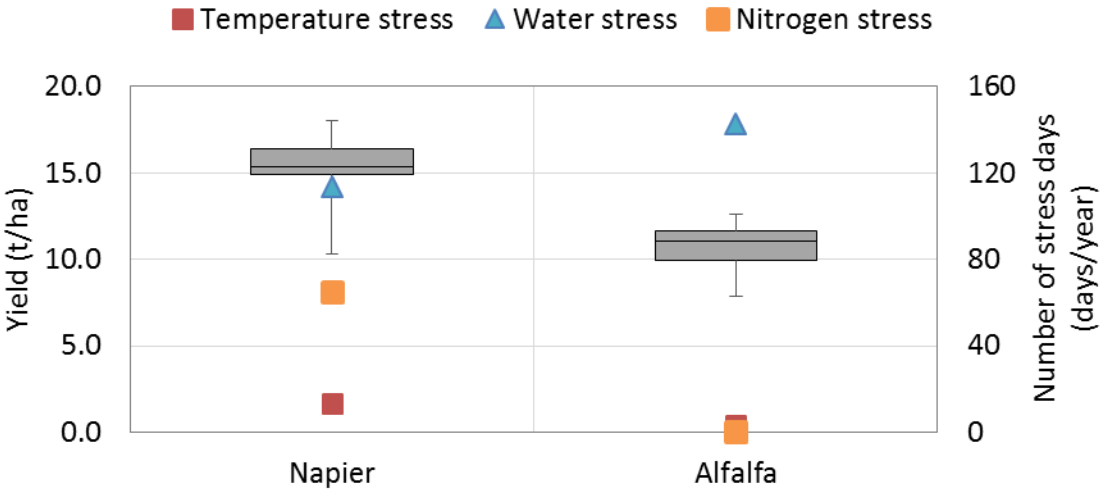


Figure 21. Yields of Napier grass and Alfalfa as perennial crops (1983 to 2013)

4.3.2 Runoff and sediment yields

Alternative scenarios 1 and 2. The effects of alternative scenarios 1 and 2 on runoff and sediment yield are shown in figures 22 and 23, respectively. Multiple cropping of maize (whether unfertilized or fertilized) did not change runoff or sediment yield at a p-value of less than 0.05. The soil type, loamy with a medium texture, has a moderate erodibility factor; however, with a nearly level slope, multiple cropping of maize (whether unfertilized or fertilized) did not show a significant runoff or sediment yield difference at a p-value of 0.05.

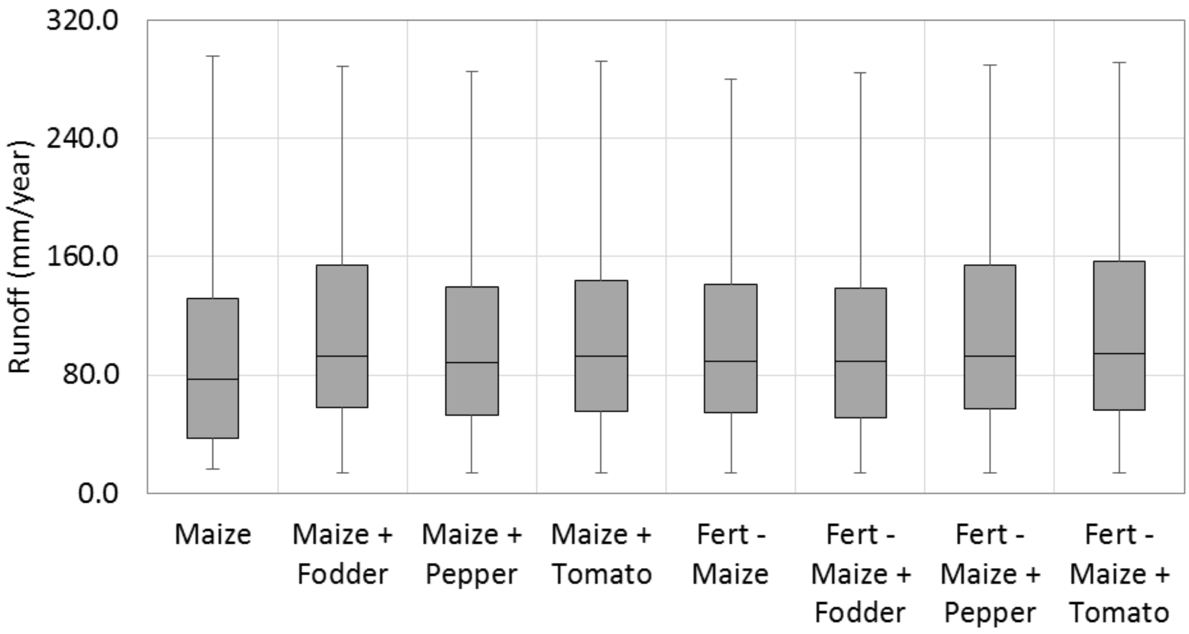


Figure 22. Runoff in alternative scenarios 1 and 2

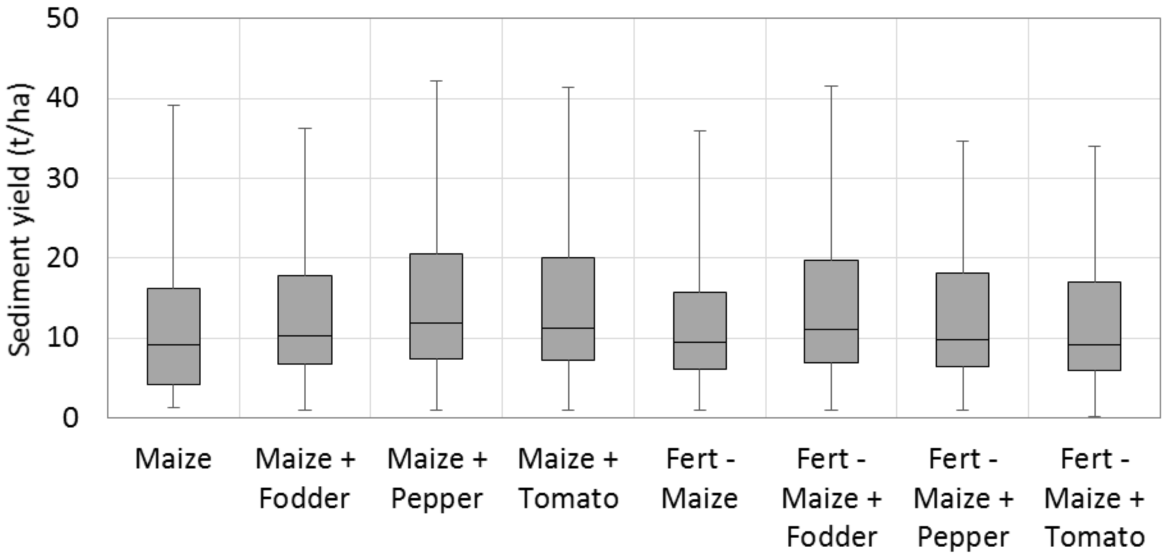


Figure 23. Sediment yields in alternative scenarios 1 and 2

Alternative scenarios 3 and 4. Figures 24 and 25 shows runoff and sediment yields in alternative scenarios 3 and 4. Multiple cropping of millet (whether fertilized or unfertilized) with irrigated fodder, pepper, and tomato did not change runoff yields at a p-value of less than 0.05. The soil type, loamy with a medium texture, has a moderate erodibility factor; however, with a nearly level slope, multiple cropping of millet (whether unfertilized or fertilized) did not show a significant runoff or sediment yield difference at a p-value of 0.05.

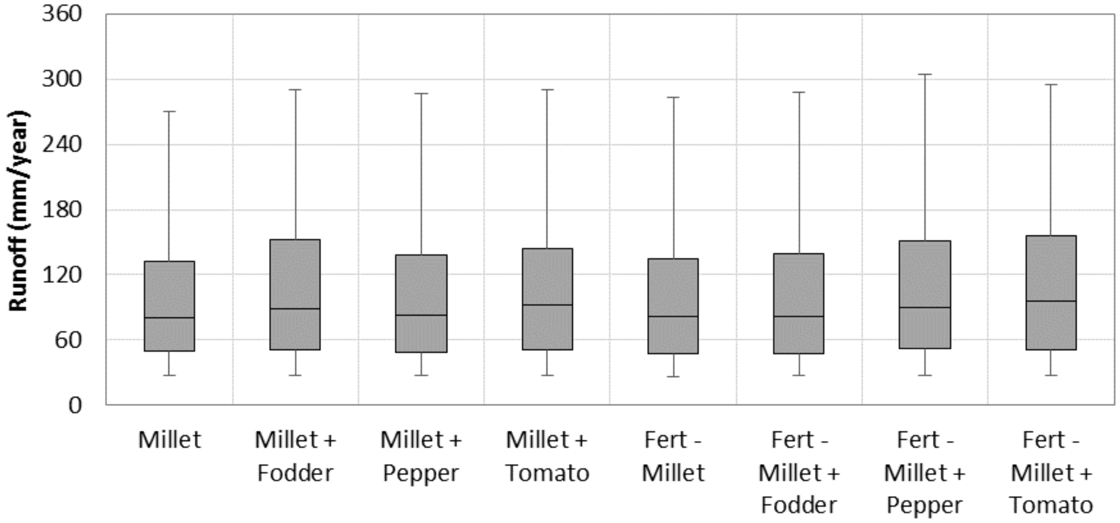


Figure 24. Runoff in alternative scenarios 3 and 4

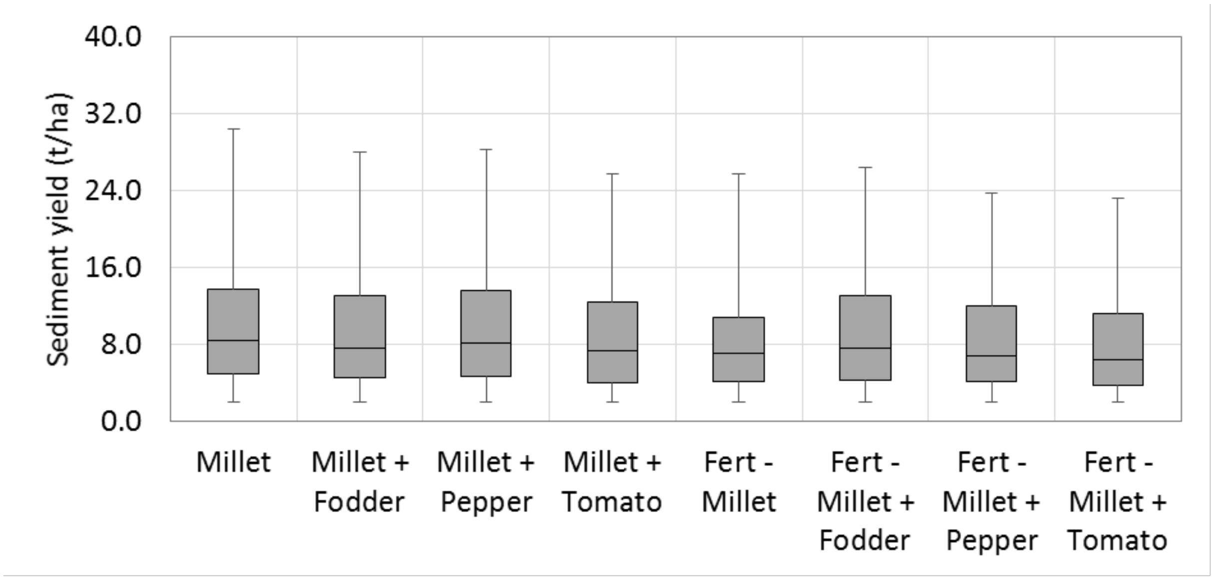


Figure 25. Sediment yield in alternative scenarios 3 and 4

Alternative scenario 5. APEX simulations indicated that continuous cropping of alfalfa and Napier grass would reduce soil erosion by 98% and 80%, respectively, compared with the baseline scenario (data not shown). In contrast, simulations indicated that continuous cropping of alfalfa and Napier grass would not significantly affect runoff as compared to the baseline scenario (fig. 26).

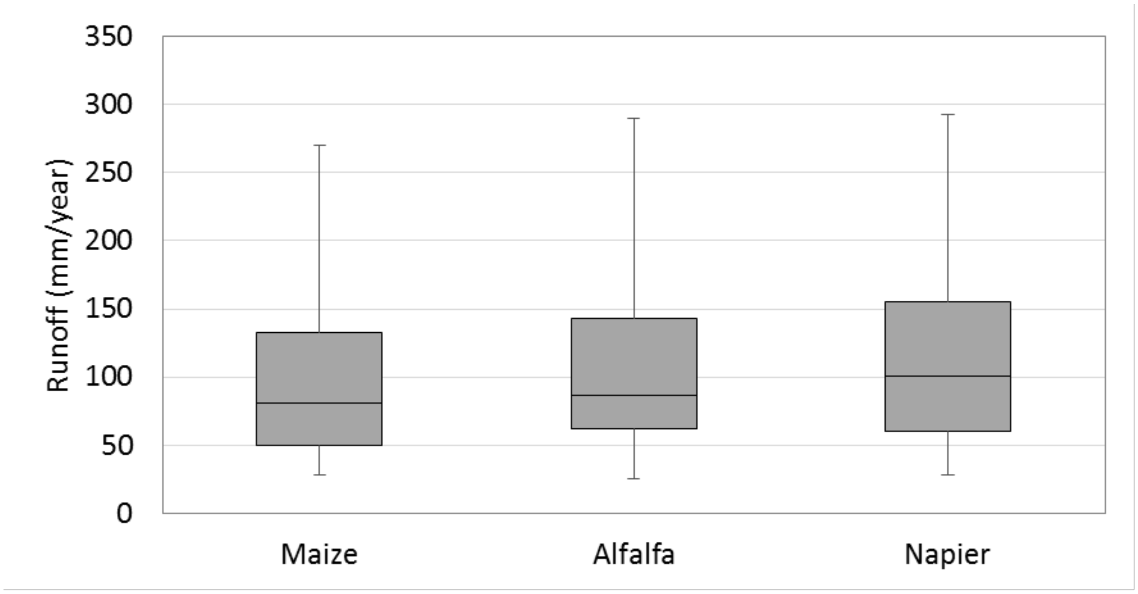


Figure 26. Runoff yields of alternative scenario 5 compared with baseline scenario

4.4 Economic analyses. The analyses that follow reference the baseline scenario and FARMSIM alternative scenarios 1-4, discussed in some detail above. The baseline scenario and four alternative scenarios are specifically defined as follows:

> Baseline (current fertilizer + no irrigation): Maize and millet are grown in the rainy 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. 1-4), maize and millet 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 maize or millet in the rainy season:

> Alt. 1: pulley irrigation + multiple cropping of maize or millet with vegetables/fodder + recommended fertilizers
>
> Alt. 2: rented, diesel-pump irrigation + multiple cropping of maize or millet with vegetables/fodder + recommended fertilizers
>
> Alt. 3: owned, diesel-pump irrigation + multiple cropping maize or millet with vegetables/fodder + recommended fertilizers
>
> Alt. 4: owned, solar-pump irrigation + multiple cropping of maize or millet 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, as these costs can vary greatly from household to household, depending on the type of well (e.g., in-field, riverine, permanent shallow well) drilled (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 five 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. A positive NPV indicates that the technology has a return greater than the assumed 10% discount rate. The NPV results, as illustrated by the cumulative distribution function (CDF) graph in figure 27a, clearly indicate the importance of investing in fertilizers and certain methods of irrigation (fig. 27a). Alternatives 2, 3, and 4 (increased fertilizer rates, coupled with diesel- or solar-pump irrigation of dry-season crops) 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 1 (increased fertilizer rates, coupled with pulley irrigation of dry-season crops) was the lowest-performing, although it performed considerably better than the baseline scenario.

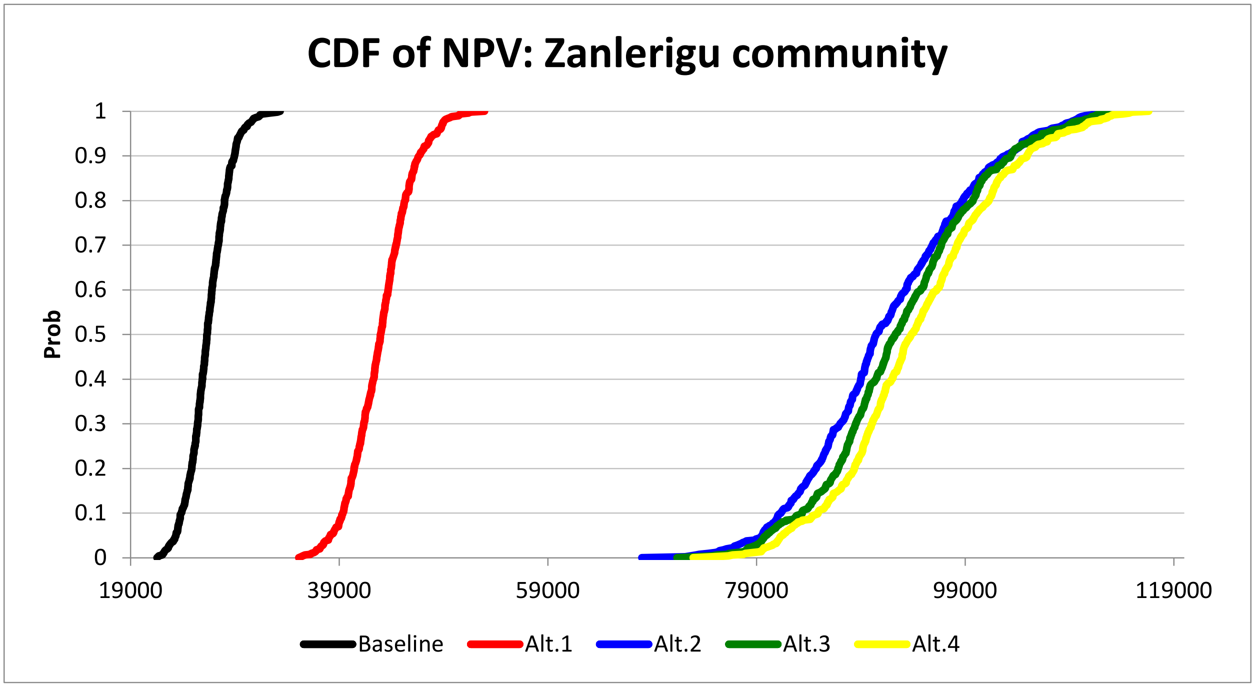


Figure 27a. Cumulative distribution function of NPV for Zanlerigu village

Legend

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

The stoplight chart below (fig. 27b) presents the probabilities in each of the six scenarios of NPV for the five-year planning horizon being less than 26,000 GH₵ (Ghanaian Cedi) (red), greater than 92,000 GH₵ (green), or between the two target values (yellow). The target values are: the average of NPV for the lowest-performing scenario (Baseline) for the lower bound; and the average of the two best-performing scenarios (Alts. 3 and 4) for the upper bound. For a farmer in the baseline scenario, there is a 42% chance that NPV will be less than 26,000 GH₵ and a 0% chance that NPV will exceed 92,000 GH₵. In contrast, for a farmer who implements alternative 2, 3 or 4 (increased fertilizer rates, coupled with diesel- or solar-pump irrigation of dry-season crops), there is a 0% chance that NPV will be less than 26,000 GH₵; moreover, the probability that NPV will exceed 92,000 GH₵ is 45%, 51%, and 60%, respectively. The main barrier for the best-performing scenario (Alt.4, 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.

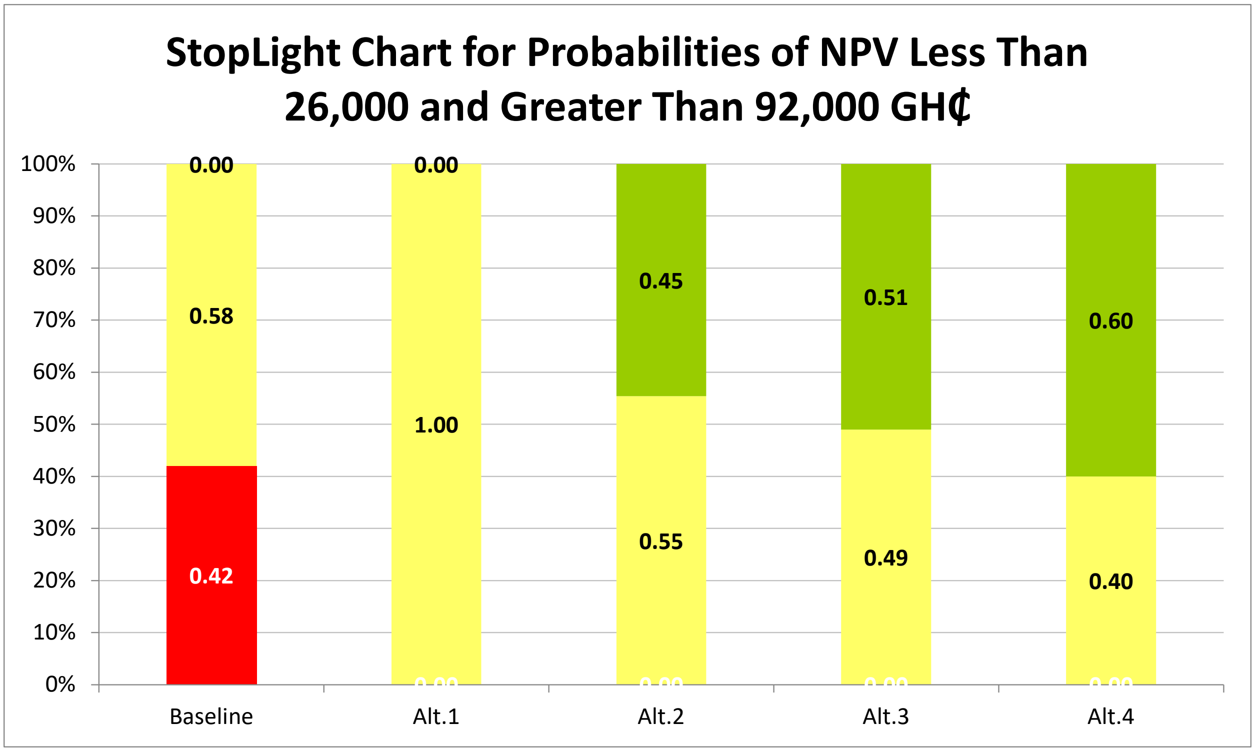


Figure 27b. Stoplight chart of NPV for Zanlerigu village

Legend

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

4.4.2 NCFI. The CDF graph for annual NCFI (fig. 28a) shows that alternatives 2, 3, and 4 (increased fertilizer rates, coupled with diesel- or solar-pump irrigation of dry-season crops) 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 1 (increased fertilizer rates, coupled with pulley irrigation of dry-season crops) was the lowest-performing, although it performed considerably better than the baseline scenario. The choice of whether to rent or own a diesel pump (alts. 2 and 3, respectively) did not have a significant effect on NCFI.

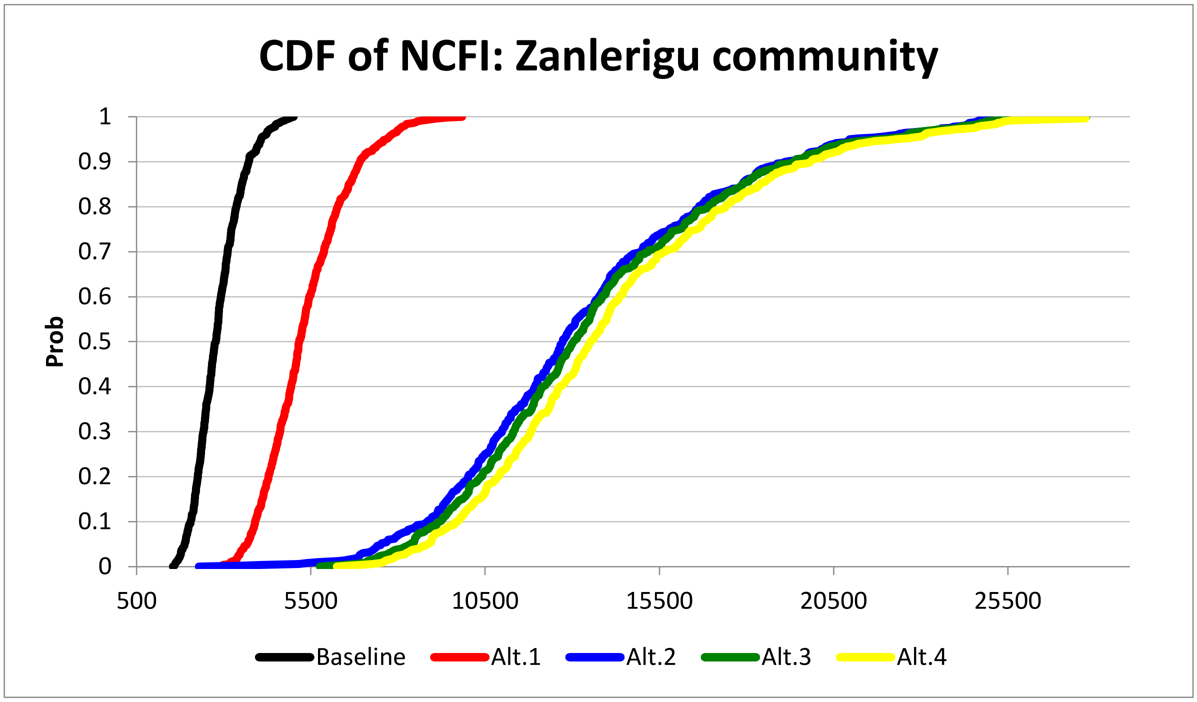


Figure 28a. Cumulative distribution function of the NCFI for Zanlerigu village

Legend

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

The stoplight chart in figure 28b illustrates NCFI in year three of the 5-year planning horizon for the baseline and four alternative scenarios. In the baseline scenario, there is a 64% chance that NCFI will be less than 3,000 GH₵, and a 0% chance that NCFI will exceed 13,000 GH₵. A farmer who adopts alternative 1 (increased fertilizer rates, coupled with pulley irrigation of dry-season crops) has only a 1% chance of generating NCFI of less than 3,000 GH₵, but also a 0% chance of generating NCFI of more than 13,000 GH₵. In contrast, for a farmer who implements alternatives 2, 3, or 4 (increased fertilizer rates, coupled with diesel- or solar-pump irrigation of dry-season crops), the probability that NCFI will exceed 13,000 GH₵ is 47%, 50%, and 57%, respectively. Alternative 4 (solar-pump irrigation) generated the highest NCFI.

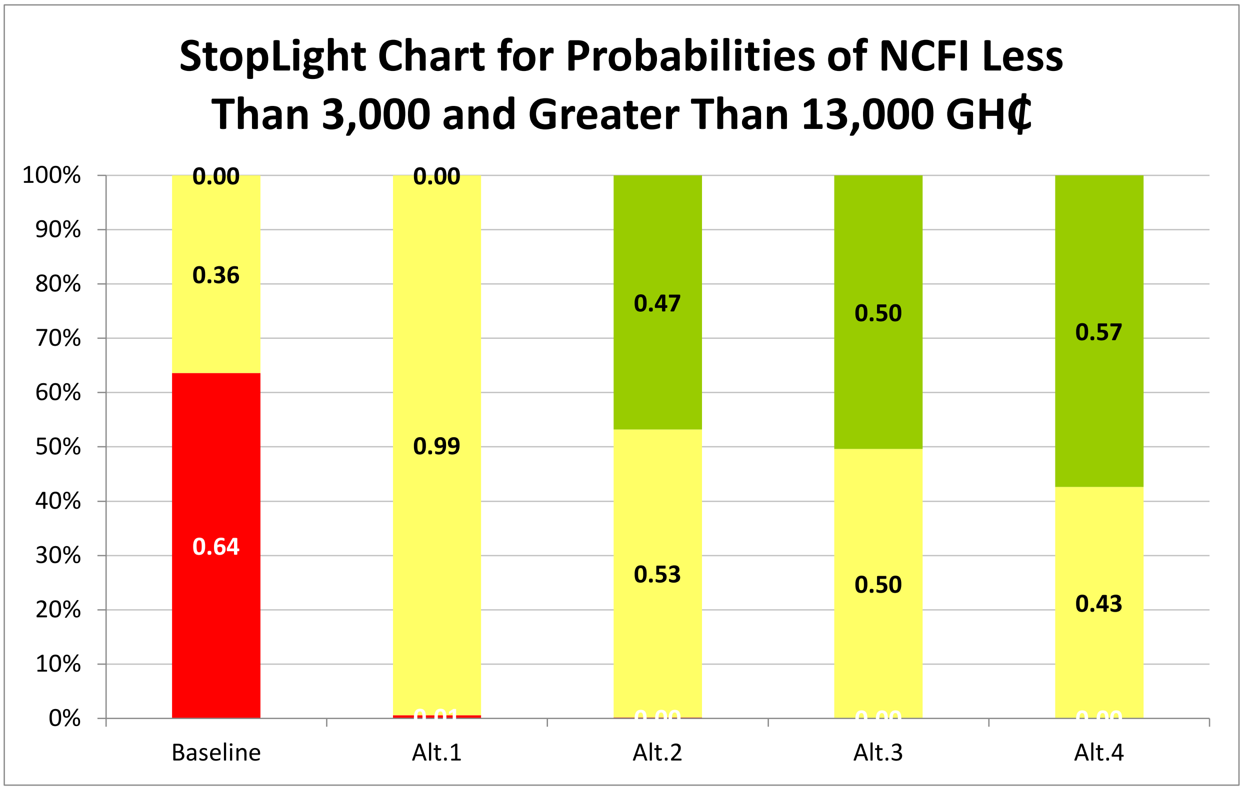


Figure 28b. StopLight chart of the NCFI for Zanlerigu village

Legend

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

4.4.3 EC. The CDF graph in Figure 29a illustrates potential EC in the fifth year of the five-year planning horizon for each of the five scenarios. The simulation results highlight once again the superior performance of alternatives 2, 3, and 4 (increased fertilizer rates, coupled with diesel- or solar-pump irrigation of dry-season crops), in that the CDF values for these three scenarios lie entirely to the right of the baseline scenario and alternative 1 (pulley irrigation), with alternative 4 (solar-pump irrigation) leading the group. These results suggest that investing in pump irrigation and adopting best agricultural practices (increased fertilizer rates) have significant potential to increase farmers' cash reserves. The baseline scenario (with no irrigation and current levels of fertilizer application) had the weakest performance.

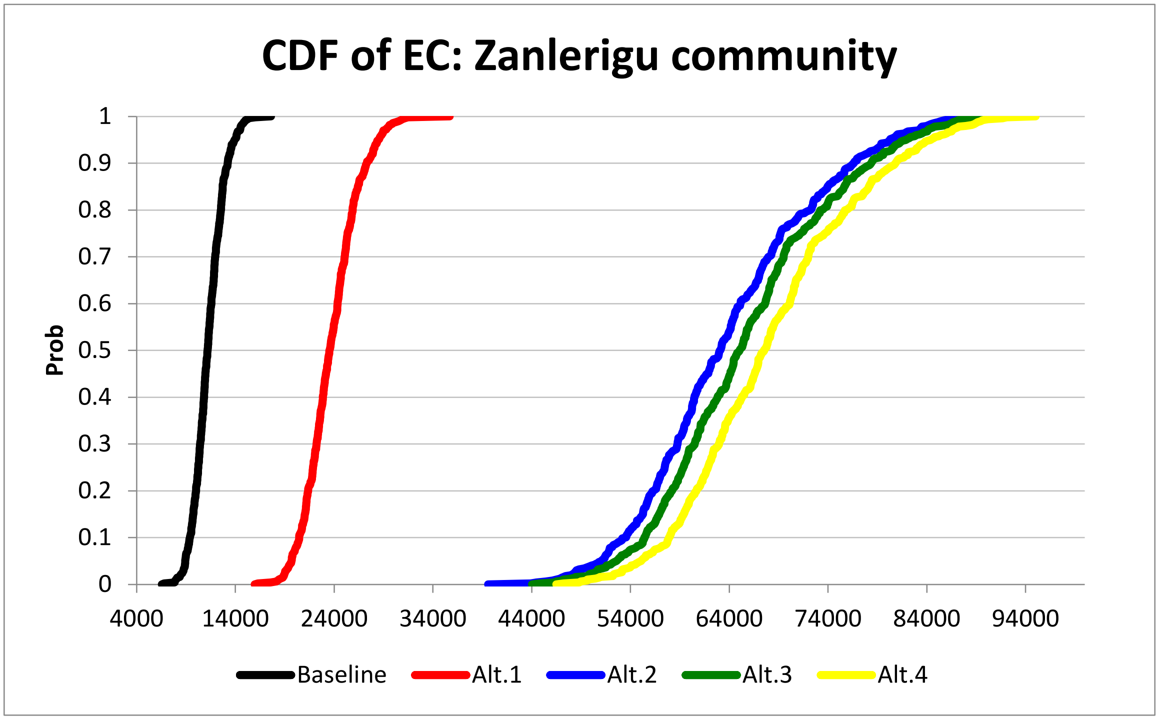


Figure 29a. Cumulative distribution function of the ending cash reserves for Zanlerigu village

Legend

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

The stoplight chart for EC reserves (fig. 29b) shows that, for a farmer in the baseline scenario, there is a 71% probability that EC in year five will be less than 12,000 GH₵ and a 0% probability that EC would be greater than 65,000 GH₵. In contrast, for a farmer who adopted alternative 2, 3, or 4 (increased fertilizer rates, coupled with diesel- or solar-pump irrigation of dry-season crops), there was a 0% probability that EC would be less than 12,000 GH₵, and a 41%, 50%, and 61% probability, respectively, that EC would exceed 65,000 GH₵. Alternative 4 (solar-pump irrigation) generated the highest EC. Alternative 1 (increased fertilizer rates, coupled with pulley irrigation of dry-season crops) produced much lower EC than alternatives 2, 3, and 4, 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.

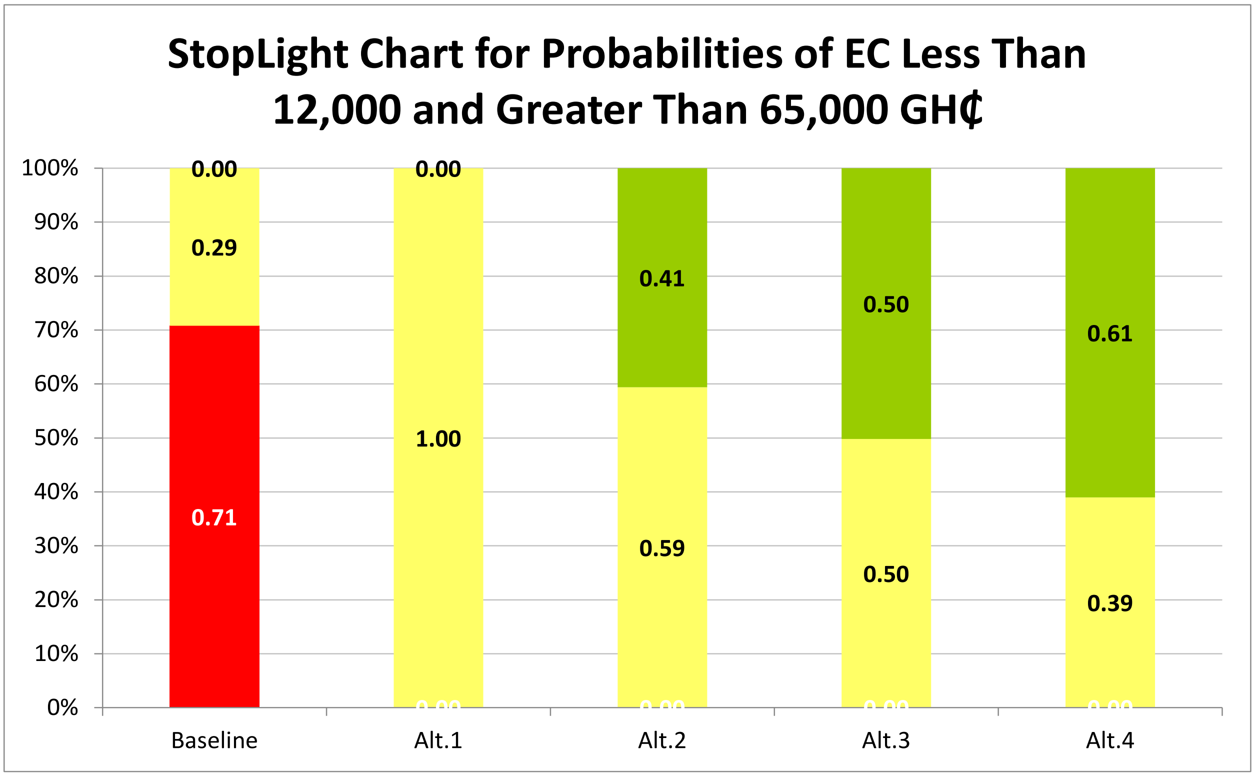


Figure 29b. Stoplight chart of EC for Zanlerigu village

Legend

Baseline : **No irrigation**
Alt.1 : **Pulley-MV**
Alt.2 : **Diesel_PR-MV**
Alt.3 : **Diesel_PO-SV**
Alt.4 : **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 and protein required for an adult; however, in the baseline scenario, levels of fat were deficient, and levels of calcium, iron, and vitamin A were merely adequate. The levels of fat increased to high levels in the alternative scenarios, and levels of vitamin A increased to high levels in alternative scenarios 2, 3, and 4 (the pump-irrigated scenarios). Calcium and iron did not show any significant improvement in the alternative scenarios, remaining at only adequate levels. Clearly, families in Zanlerigu would benefit food supplements (whether obtained through purchase or farming) to increase their daily intake of calcium and 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 Zanlerigu, ILSSI proposes implementing SSI, using shallow groundwater 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 of watershed-scale hydrology indicated that there is large water resources potential in the Zanlerigu watershed. The total annual groundwater recharge was more than 112 mm, and the annual generated surface runoff was more than 73 mm. However, the average annual irrigation water requirement for cultivating dry-season pepper and Napier grass exceeded the average annual shallow groundwater recharge. Implementation of SSI for dry-season pepper and Napier grass production caused a modest reduction in the monthly stream flow. Peak flows and low flows also decreased with implementation of the irrigated pepper/Napier grass scenario.

Since the shallow groundwater recharge was not sufficient to meet the irrigation water requirement, we would recommend combining irrigation from the shallow groundwater aquifer with irrigation from other water sources. For example, water-harvesting ponds (dugouts), used in other watersheds for SSI purposes, could be used to store and capture surface runoff for SSI in the Zanlerigu watershed. We would also recommend selecting water-efficient crops for dry-season cultivation in order to minimize reductions in stream flow. Analyses of potential dugout sites and scale, likely costs and benefits of irrigating from dugouts, and recommendations as specific water-efficient crops for cultivation, were beyond the scope of this study but could be addressed in future research.

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizers would increase crop yields substantially without a considerable impact on the environment. More specifically, the addition of 50 kg/ha of urea and 50 kg/ha or DAP doubled maize and millet yields without significantly affecting runoff or sediment yield. Proper understanding and use of multiple-cropping combinations could also increase crop yields and improve soil health, although some combinations would probably decrease productivity. For the fertilizer application scenarios simulated in this study, multiple cropping of rainy-season maize and millet with dry-season fodder (oats/vetch) increased simulated maize and millet yields substantially by increasing residual nitrogen, and did not adversely affect fodder yields. Multiple cropping of the grain crops with tomato increased simulated maize and millet yields by lesser amounts; however, tomato yields decreased with multiple cropping. Finally, high temperature stress was also a major factor limiting yields of certain crops, such as pepper and oats. The yield of pepper planted as a rain-fed crop in the cooler season was double that of irrigated, dry-season pepper. Planting temperature-sensitive crops in the cooler season would therefore also optimize yields.

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 Zanlerigu 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, five scenarios (including the baseline, non-irrigated scenario) were simulated. The pulley-irrigated, multiple-cropping scenario did not differ greatly from the baseline, non-irrigated scenario. In contrast, the scenarios that implemented multiple cropping of grain crops 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). Given the lower maintenance and environmental costs of solar pumps, simulation results suggest that investments in solar water-lifting technologies will pay dividends in the long run.

The simulated, improved cropping systems resulted in improvements in farm-family nutrition. While levels of fat were deficient and levels of calcium, iron, and vitamin A were merely adequate in the baseline, non-irrigated scenario, in the alternative scenarios, levels of fat and vitamin A exceeded daily requirements (though levels of calcium and iron remained at only adequate levels). We would propose expanding the types of crops irrigated in the dry season to further 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 Zanlerigu watershed

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

Maize Practice	Dates	Amount	Millet 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	27-Oct	

Crop management for the SSI (ex ante) scenario in the Zanlerigu 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 millet/tomato rotation:

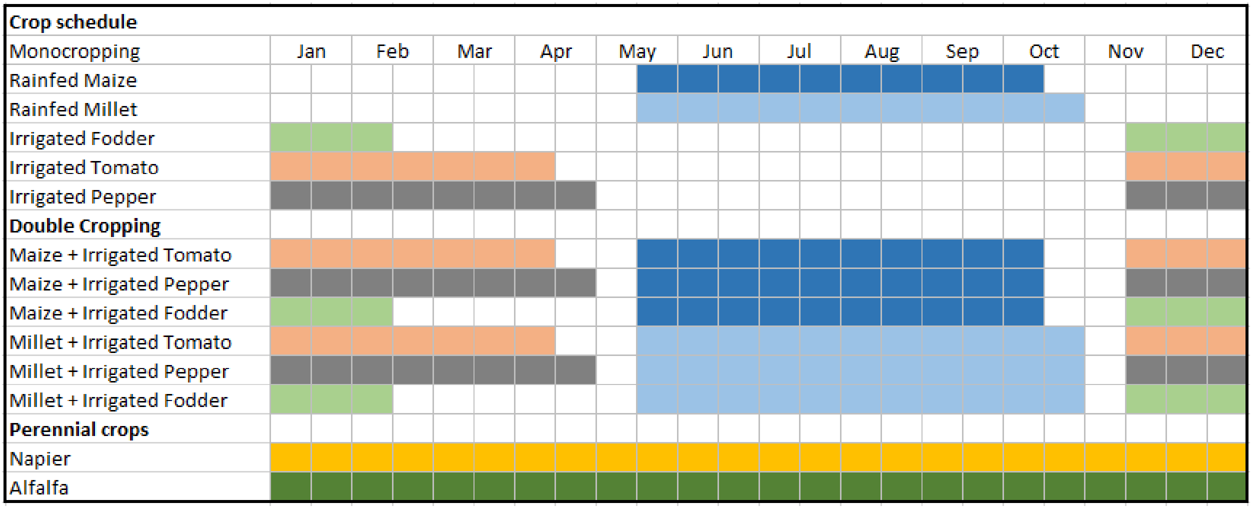
Millet practice	Dates	Amount	Tomato Practice	Dates	Amount
Tillage	15-May		Tillage	20-Nov	
Tillage	1-Jun		Tillage	5-Dec	
Tillage	15-Jun		DAP fertilizer application	5-Dec	50 kg/ha
DAP fertilizer application	15-Jun	50 kg/ha	Planting	5-Dec	
Planting	15-Jun		1st urea fertilizer applic.	5-Dec	25 kg/ha
1st urea fertilizer applic.	15-Jul	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	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 Zanlerigu watershed, as simulated with APEX



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

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

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). Millet schedule with and without fertilizer

Millet 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). Tomato, pepper and fodder schedule

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

d) 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

e) Napier grass schedule

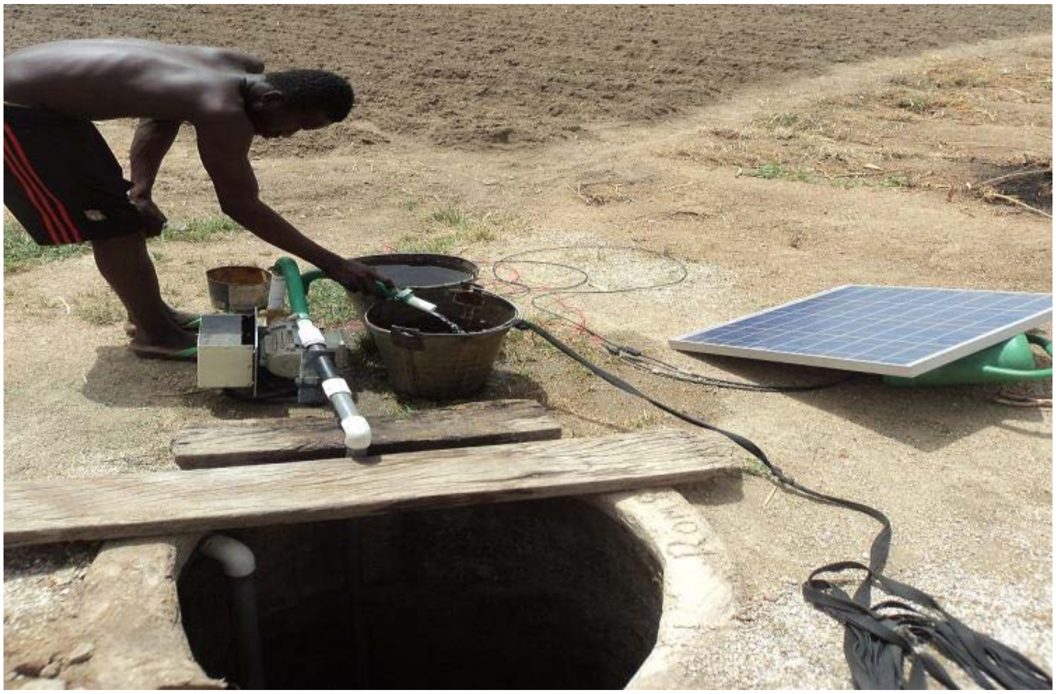
Year	Operations	Date	Notes
1st year	Tillage	1/1	
1st year	Tillage	1/20	
1st year	DAP fertilizer application	1/20 (100 kg/ha)	One time only
1st year	Urea fertilizer application	1/20 (100 kg/ha)	At planting
1st year	Planting	1/20	
1st year	1st Cut	4/20	First cut after 3 months
1st year	Urea fertilizer 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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