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Ex Ante Analysis of Small-Scale Irrigation Interventions in Mvomero

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USAID Feed the Future Innovation Laboratory for Small-Scale Irrigation

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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 Mkindo watershed, in the Mvomero district of the United Republic of Tanzania. The annual crops yields produced in the area are far below global average yields. Farm-family livelihoods are derived from main cereal crops produced in the rainy season. Vegetables such as tomato and cabbage 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 Mvomero, ILSSI proposed implementing SSI, using diverted river water, to maximize cultivation of high-value vegetable and fodder crops in the dry season and productivity of the rice crop. ILSSI evaluated the proposed SSI interventions by simulating and comparing five alternative farming systems:

i. continuous cropping of traditional grains (maize and rain-fed rice) grown during the main rainy season, using current (minimal) fertilizer rates and current (minimal) irrigation;
ii. multiple cropping of rainy-season grain crops (rain-fed rice and maize) with several irrigated, dry-season crops, using current (minimal) fertilizer rates;
iii. multiple cropping of rainy-season maize, fertilized at higher rates, with several irrigated, dry-season crops;
iv. cultivation of a perennial fodder crop (e.g., Napier grass) on pasture land; and
v. continuous cropping of an irrigated rice crop using the System of Rice Intensification (SRI) method of cultivation.

For purposes of the simulations, APEX and FARMSIM chose tomato, cabbage 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 Mkindo watershed. Agricultural land comprises a relatively small percentage (just 24.86%) of total land in the watershed. Accordingly, the total annual volume of irrigation water withdrawn in the watershed would be less than 5.9 million m^3, or just 14% of the annual stream flow leaving the watershed. Moreover, simulations indicated that proposed SSI interventions would reduce average monthly stream flow by only 3%, and that peak and low flows would not be affected by the withdrawal of irrigation water from rivers. This suggests that the proposed SSI interventions are sustainable, and would not compromise the environmental health of the watershed. Because suitable fields far from rivers receive less irrigation water than those close to rivers, the proposed SSI interventions will require development of advanced surface water diversion and transfer technologies and/or wells to sufficiently irrigate fields located far from the rivers.

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizer would increase crop yields substantially and decrease the soil loss from erosion. 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 if fertilization rates were inadequate. For the fertilizer application scenarios simulated in this study, multiple cropping of maize with tomato increased the nitrogen stress days for both crops and significantly reduced simulated yields of both crops, suggesting that increased fertilization amounts should be considered for multiple cropping of maize with tomato. In contrast, multiple cropping of maize with fodder significantly increased simulated maize yields and did not significantly affect fodder yields.

Simulations also showed that SRI rice production would result in higher crop water productivity compared to traditional rain-fed rice. These results suggest that, as concluded by Worqlul et al. (2015), SRI rice is the best alternative in places like Tanzania and many parts of Africa where there is suitable land for agricultural production but limited access to water. Simulations also indicated the sensitivity of SRI rice yields to drying and wetting periods.

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 Mkindo village in the Mvomero district. The scenarios that produced by far the highest net present value, net cash farm income, and ending cash reserves were those that implemented continuous cropping of SRI rice (in combination with multiple cropping of fertilized maize with either irrigated vegetables and fodder, or with irrigated vegetables only). The most preferred scenario in terms of income generation was the one that implemented SRI rice and multiple cropping of fertilized maize with irrigated vegetables only. In contrast, the scenario that included multiple cropping of rain-fed rice (rather than continuously cropped SRI rice) with irrigated vegetables and fodder did not differ greatly from the baseline, non-irrigated scenario.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies persisted (especially in vitamin A) 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 relatively modest percentage of cropland in the area (just 24.86% of the total watershed area) also limits the expansion of SSI and cultivation of additional crops in the Mkindo watershed.

Our analysis raised a number of issues to be resolved in future modeling and field research. These include the need to identify: (1) the potential for use of shallow groundwater from SSI in areas too distant for use of surface water; (2) appropriate fertilizer amounts for more intensive cropping systems involving production of irrigated vegetable, fodder, and grain crops in the dry season; and (3) appropriate management of fertilizer and harvest practices for irrigated fodder production. 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 core driver of the economy in developing countries like Tanzania, despite the fact that subsistence farming suffers from low yields and high vulnerability to climate change (Awokuse and Xie 2015; Tibesigwa and Visser 2015). Developing countries must strive hard to meet demand caused by increasing populations and economic growth; however, as in other parts of the world, farming systems in Tanzania 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 small-scale, irrigated agriculture 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 Mkindo watershed, located in the Mvomero district of the Morogoro Region of Tanzania. Temperatures in the district are ideal for cropping year-round, but the dramatic shift in rainfall that occurs between the major and minor rainy seasons and the dry season restricts rain-fed cropping to the rainy seasons. Annual crops yields produced in the Mvomero district are far below global average yields. Major factors contributing to low crop production include erratic weather conditions, low soil fertility, and ineffective management practices.

Information about Mvomero'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 traditional grains (maize and rain-fed rice) grown during the main rainy season, using current (minimal) fertilizer application rates and current (minimal) irrigation. The proposed SSI interventions simulated with SWAT, APEX and FARMSIM used diverted river water to enable multiple cropping of the rainy-season grain crop (rain-fed rice or maize) with several irrigated, dry-season crops. All three models simulated application of improved fertilizer rates on the maize crop. To provide more detail at the field scale, APEX and FARMSIM also simulated the cultivation of certain perennial crops (e.g., Napier grass) on pastureland, and using diverted river water to enable continuous cropping of SRI rice. FARMSIM was used to simulate the effects of these alternative scenarios on farm-scale economics.

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 Mkindo watershed is located at 6°30’ 20” S, 37°45’25” E in the Movmero district of the Morogoro region of Tanzania (fig. 1).

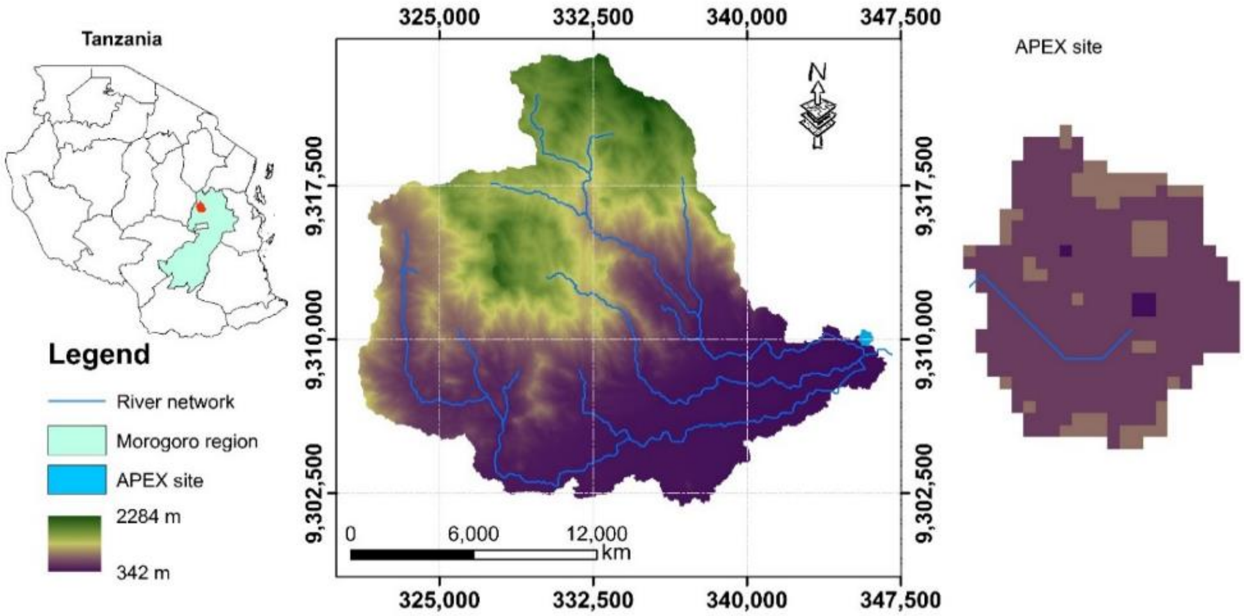


Figure 1. Mkindo watershed boundary, main streams and Subarea 617, simulated with APEX.

The watershed covers a 32,131.5-ha area, and its outlet is located downstream of Mkindo bridge, where there is a stream flow gauging station. Three types of land use were identified in the Mkindo watershed: cropland (24.86%), forestland (24.16%), and bush land (50.98%) (SRTM 2015). Two types of soils were identified: clay-loam (71%) and loam (29%) (FAO&ISRIC, 2013). The average percent slope of the watershed, computed from 30m-resolution Enhanced Shuttle Land Elevation Data, was approximately 14%. 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%.

The main crops cultivated in the area are rice, maize and tomato, all cultivated in the major and/or minor rainy seasons. Traditional, rain-fed rice is cultivated in lowlands close to the river networks and irrigated once every month, except when rainfall is highest. Maize is cultivated in the uplands. Vegetables such as tomatoes and cabbage, and fodder such as vetch/oats and Napier grass, are cultivated in limited quantities using only minimal, if any, irrigation. Agricultural inputs (fertilizer, irrigation, improved seeds) are applied at minimal levels. Irrigation water is mainly available from surface water through rivers and shallow wells. Small-scale farmers primarily use buckets for lifting water and traditional canals for conveying irrigation water to their farms.

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

3.2.1. Hydro-meteorological data. Thirty-one years of daily weather data, from 1980 to 2010, were collected from the Tanzanian Meteorological Agency (TMA) via our partners at Sokoine University of Agriculture (SUA). These data included rainfall, temperature (min/max), relative humidity, sunshine hours (solar radiation), and wind speed. SWAT and APEX used the same weather dataset. Figure 2 shows the boxplots of the monthly average meteorological data for the watershed for the period from 1980 to 2010.

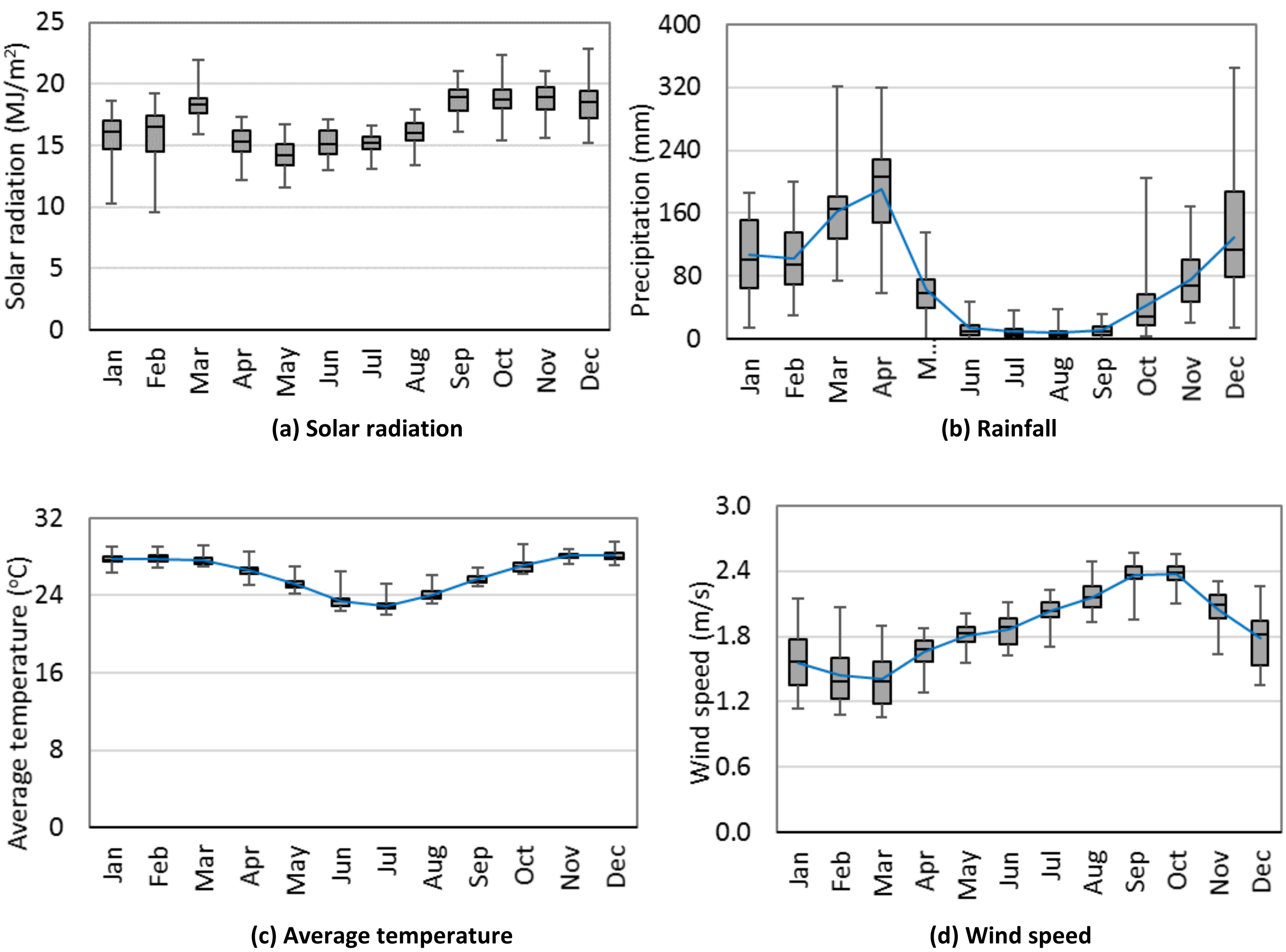


Figure 2. Monthly average weather data from a synoptic station from 1980 to 2010 (TMA 2015). The rectangle represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

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.

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, global soil map from FAO-UNESCO Soil Map of the World (FAO&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 the Wami-Ruvu Basin Water Office (WRBWO 2015) via our partners at SUA.

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) data from the FAO Statistics Division (FAOSTAT), including calculated crop yields aggregated for all of Tanzania from 1961 to 2013 (http://faostat.fao.org/site/567/desktopdefault.aspx#ancor). The FAOSTAT dataset does not include crop management practices; and

c) a 2013 survey by the International Food Policy Research Institute (IFPRI) of households in the Mkindo 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 1981 to 2010 for maize and rice.

Table 1. SPAM 2005 cycle and FAOSTAT average crop yield (1981 to 2010) (t/ha) for maize and rice.

Dataset	Country	District	Maize (t/ha)	Rice (t/ha)
SPAM (2005)	Tanzania	Mvomero	1.40	1.80
FAO (1981 to 2010)	Tanzania	--	1.50	1.73

3.3 Methods

3.3.1 <u>SWAT and APEX model setup and calibration</u>. First, the SWAT model was set up for the entirety of the Mkindo watershed. The 32,131.5-ha watershed was subdivided into 1160 subbasins with a mean area of approximately 25 ha, so as to accommodate small-scale agricultural water management interventions during the ex-ante analysis. Using SWAT, flow and sediment were simulated by transferring the calibrated and validated model parameter sets of the nearby gauged river, the Wami River. Stream flow data for SWAT calibration were obtained from the Dakara and Makata river gauging stations in the Wami Basin (fig. 3). The area between the Dakara and Makata river gauging stations was chosen for calibration since we have observed stream flow for these two gauging stations and to better represent the hydro-ecological situation of the Mkindo and Rudewa watersheds. The catchment area for the watershed where calibration was performed is 6327.75 km^2. For the calibrated watershed, 57.4% is forested land, 14.5% is bush land, 14.8% is agricultural land, and 12% is grazing land. The remaining land is covered by residential area, wetland and barren land. In the agricultural land where the slope is <8%, rice is cultivated.

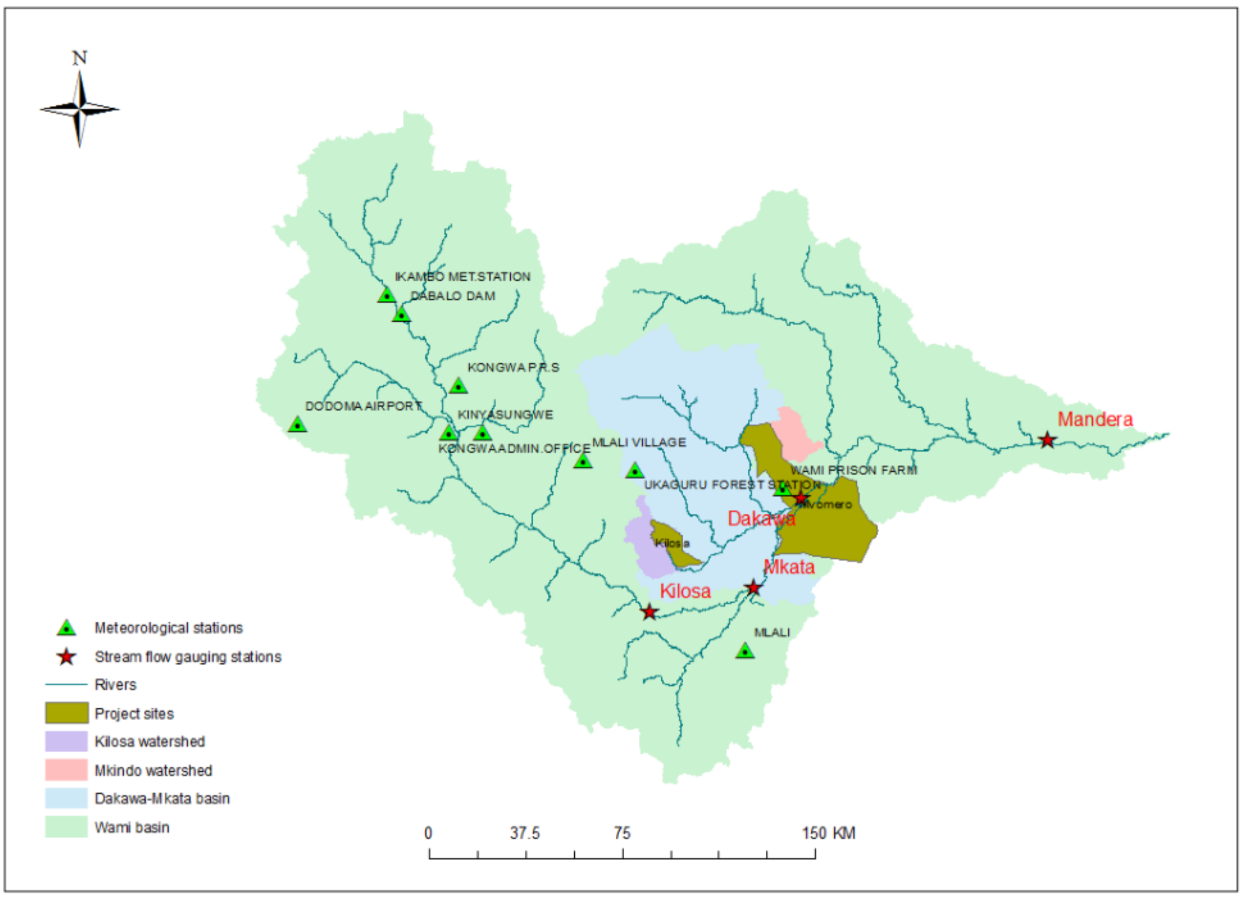


Figure 3. Location of the Mkindo watershed in the Wami basin.

For APEX, a sub-watershed dominated by agricultural land (subarea 617, equivalent to SWAT's subbasin 617) was selected (fig 1). 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 subarea 617 as estimated by SWAT were used to calibrate the APEX model. The calibration was achieved by using the automatic calibration tool APEX-CUTE (auto-Calibration and UncerTainty Estimator) (Wang and Jeong 2015). After capturing flow and sediment of SWAT, APEX crop parameters were calibrated to match maize and rice yields of the SPAM dataset for the 2005 cycle. As a validation, APEX-simulated crop yields from 1981 to 2010 were compared with FAOSTAT's calculated crop yields using standard statistical measures, including root-mean-square error and percent difference.

The sub-watershed selected for APEX is located close to the outlet of the Mkindo watershed (fig. 1), and is approximately 56 ha in area, with elevation varying from 2410 to 2520 mamsl. The average percent slope of the sub-watershed is approximately 3% (USGS EarthExplorer). Simulated flow and sediment were calibrated from 1985 to 2010. 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 management schedules and fertilizations (type, rates, and application dates), crop yields for maize and rice were simulated to match with the 2005 SPAM crop yields through crop parameter calibration.

3.3.2 Alternative scenarios simulated with SWAT and APEX. Alternative scenarios simulated with SWAT and APEX included: using diverted river water to enable multiple cropping of the rain-fed grain crops (rice and maize) in the rainy season with several irrigated crops in the dry season; and fertilizing the maize crop at improved (higher) rates. In evaluating the effects of the proposed SSI interventions at the watershed scale, SWAT simulated multiple cropping of: maize with tomato; and rain-fed rice with a second crop of irrigated, traditionally-grown rice. To provide more detail at the field scale, APEX simulated: multiple cropping of maize with irrigated tomato, cabbage, and fodder (oats/vetch); continuous cropping of Napier grass and alfalfa as perennial crops on pasture land; and continuous cropping of SRI rice as an alternative to traditional, rain-fed rice.

In many developing countries, it has become a common practice to protect the pasture lands from grazing animals, simultaneously cultivating good forage for the animals and protecting the land from degradation. For these reasons, and because we did not want to allocate any of the watershed's scarce agricultural lands (just 24.86% of the watershed area) to the production of fodder, we decided to implement cultivation of certain perennial fodder crops (e.g., alfalfa and Napier grass) on the pasture lands.

The SRI method for rice cultivation was introduced in Tanzania in 2009 to strengthen the country's food security, and is practiced in Mvomero and other areas of Tanzania. Contrary to the traditional approach of growing rice in flooded plots, the SRI method requires less water and labor by following a strict protocol of alternating wetting and drying periods during the growing season. Under the SRI method, water is channeled through canals by gravity to paddy fields, which are flooded to a shallow depth for a period of 3 to 6 days, and then left to dry for a period of 3 to 8 days, depending on the soil and climate conditions (Aune et al. 2014; Satyanarayana et al. 2007). SRI management practices simulated with APEX were established based on close communication with local experts and SRI rice guideline practices by Katambara et al. (2013). For this study, we simulated two different SRI schedules: a 3-day wetting period followed by a 5-day drying period; and a 3-day wetting period followed by a 7-day drying period.

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 Mkindo village for five years to provide an economic perspective on promising SSI interventions identified by SWAT and APEX simulations. The majority of the population in Mkindo village derive their livelihoods from crop and livestock production. A 2015 IFPRI survey indicated that the major crops grown, by area, in Mkindo village are paddy rice (952 ha) and maize (135 ha), on an estimated total cropland of 1337 ha (rain-fed and irrigated). Vegetables such as tomatoes and cabbage are produced as well, and their areas can be expanded with irrigation during the dry season. Pastureland in Mkindo is limited, occupying only about 148 ha. The main types of livestock produced are chickens, with a limited number of goats.

In addition to the baseline scenario, FARMSIM simulated three alternative scenarios, each implementing SSI, using diverted river water, on irrigable land in Mkindo (about 1200 ha). In the first alternative scenario, irrigable land is cultivated with grain crops (rain-fed rice and fertilized maize, allocated according to the slope of the field) in the rainy season, and irrigated vegetable and fodder crops (tomato, cabbage and vetch/oats) in the dry season. In the second and third alternative scenarios, SRI rice is introduced as an irrigated crop. Because of an overlap in growing seasons between SRI rice and other dry-season crops, SRI rice is continuously cropped except in the wet season, during which rain-fed rice is cultivated. In the third alternative scenario, all irrigable land not allocated to the SRI rice crop is cultivated in the dry season with tomatoes and cabbage; fodder is not grown. (The three alternative scenarios simulated with FARMSIM are specifically defined in section 4.4 below.)

In each of the alternative scenarios, dry season crops were irrigated as required to prevent water stress, and maize was fertilized at improved rates (50 kg/ha of urea, in split application, and 50 kg/ha of DAP). A perennial crop, Napier grass, was simulated alongside the other crops in each of the three alternative scenarios, but required only minimal irrigation; accordingly, we do not discuss the crop in detail here.

The FARMSIM model was run 500 times for each of the four scenarios—the baseline scenario and three alternate scenarios—to sample variation in crop yields due to weather and other stochastic variables. To determine which of the four 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. The performance of the four 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. Calibration of the SWAT model was challenging, as the observed stream flow data were not reliable. First, the peaking of the observed stream flow dates lagged by more than a month. For example, rainfall peaked in March of 2008, but observed stream flow peaked in April 2008 (fig. 4). Second, in some time periods, rainfall amounts did not produce any observed stream flow. For example, in February to March of 2009, there was a monthly rainfall of more than 100 mm; however, negligible observed stream flow was reported.

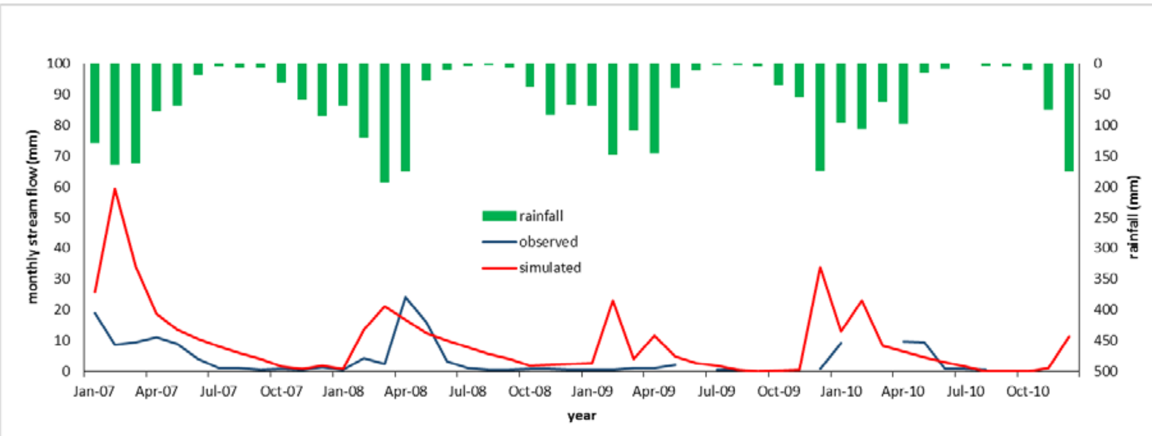


Fig. 4. Observed rainfall vs observed and simulated stream flow at the outlet of the calibrated watershed. Note: the axis for the rainfall is reversed.

Using various techniques, we were able to calibrate the model reasonably well. First, since observed stream flows were less than simulated stream flows—suggesting that stream water was being diverted, possibly for the purpose of irrigating rice—detailed management for rice cultivation was implemented with the SWAT model, including impounding, irrigating and releasing the irrigated water. Initially, irrigation was implemented in areas with slopes of less than 2%, or approximately 4.2% of the calibrated watershed area; however, observed stream flow remained significantly lower than the simulated flow, suggesting that the irrigated area was still larger. Thus, we implemented rice cultivation on agricultural fields with slopes of less than 8%, or 13.9% of the calibrated watershed area. For areas with slopes between 2% and 8%, land management practices (such as reducing the slope length) were implemented to make the area suitable for rice cultivation. Second, since much of the area in the watershed is forested land, hydrological processes in the forest were carefully calibrated. For example, high canopy storage in forested areas affects evaporation from the watershed. Thus, evaporation in the watershed was used as a guiding parameter, in addition to crop yield. Finally, the model was further fine-tuned to reproduce the low flows. Ultimately, SWAT was able to produce stream flows consistent with the rainfall pattern (fig. 4). Table 2 presents the calibrated parameters for Mkindo watershed.

Table 2. Calibrated SWAT parameters for the Mkindo watershed.

No	Model Parameters	Fitted parameter value
1	*r_CN	5%
2	v_Esco	0.7
3	v_alfa_bf	0.007
4	v_GW_Delay	10
5	v_GWQMN	1000
6	v_CANMAX (only for forested lands)	15
7	v_SL_SUB (RICE_slp2-8%)	75
8	HRU_SLP (RICE_slp2-8%)	0.01
9	USLE_P (RICE_slp2-8%)	0.7
10	CANMX	15

**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 0.73 and R-square value of 0.74. Figure 5 shows the comparison of APEX and SWAT flow simulation. The performance of the model was not a surprise, as both models share the same input datasets for land-use, soil, elevation, weather, and crop management. Both SWAT and APEX also 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).

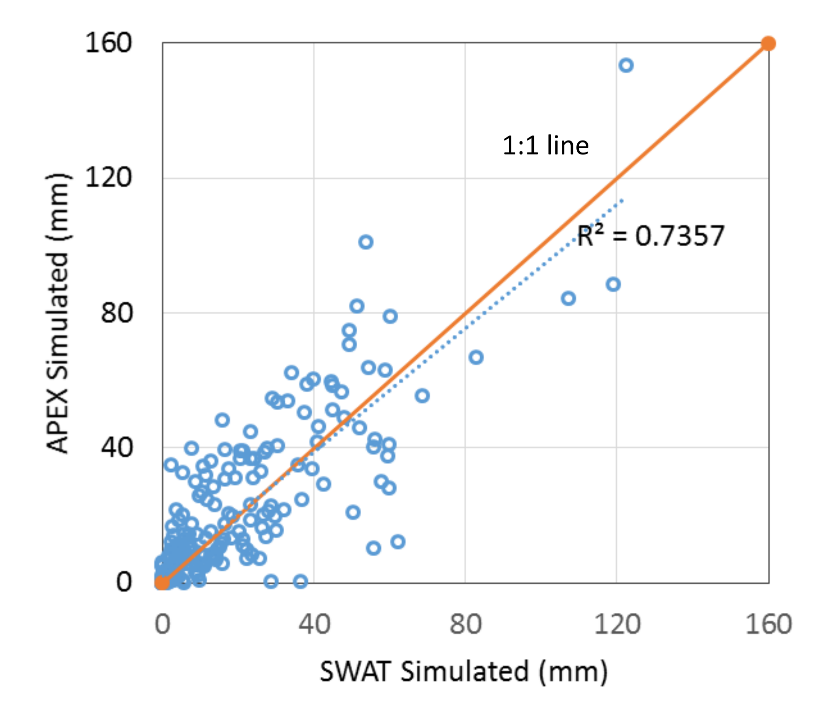


Figure 5: Scatter plot of SWAT and APEX simulated flow for Mkindo watershed

Figure 6 illustrates the general water balance components of the watershed.

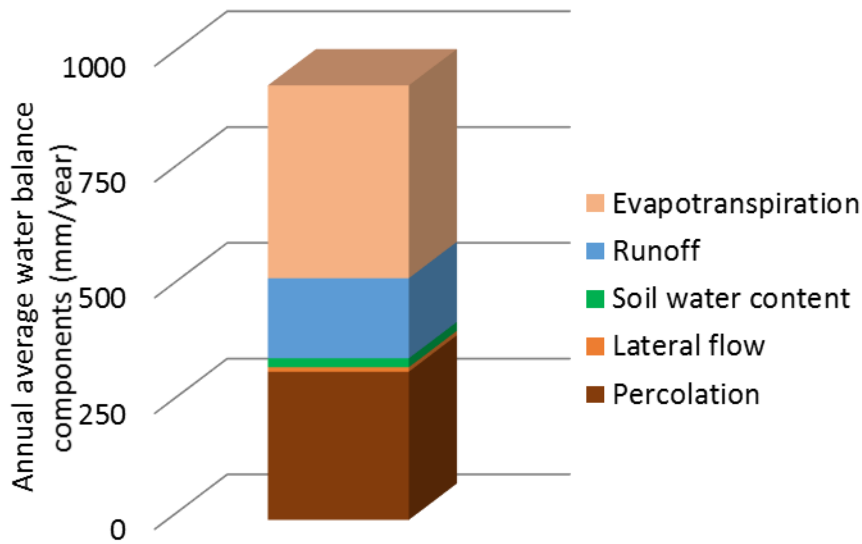


Figure 6. Water balance components of the calibrated APEX model for Mkindo watershed

4.1.3 Base period crop yield simulation. APEX captured the observed yields of maize and rice for the year 2005 well, with 4.48% and 1.69% differences from reported yields in SPAM, respectively. As a validation, simulated crop yields for the baseline were compared with the FAOSTAT calculated crop yields from 1981 to 2010.

Figure 7 shows the boxplot of APEX simulated crop yields and FAOSTAT calculated crop yields, with the SPAM 2005 crop yields plotted as diamonds. For the study period, APEX and FAOSTAT maize and rice yields differ by 7% and 15% yield respectively; RMSE are 0.5 t/ha and 0.4 t/ha for maize and rice, respectively. The FAO yield estimate has a higher variance than the APEX result, as it is estimated for the whole of Tanzania.

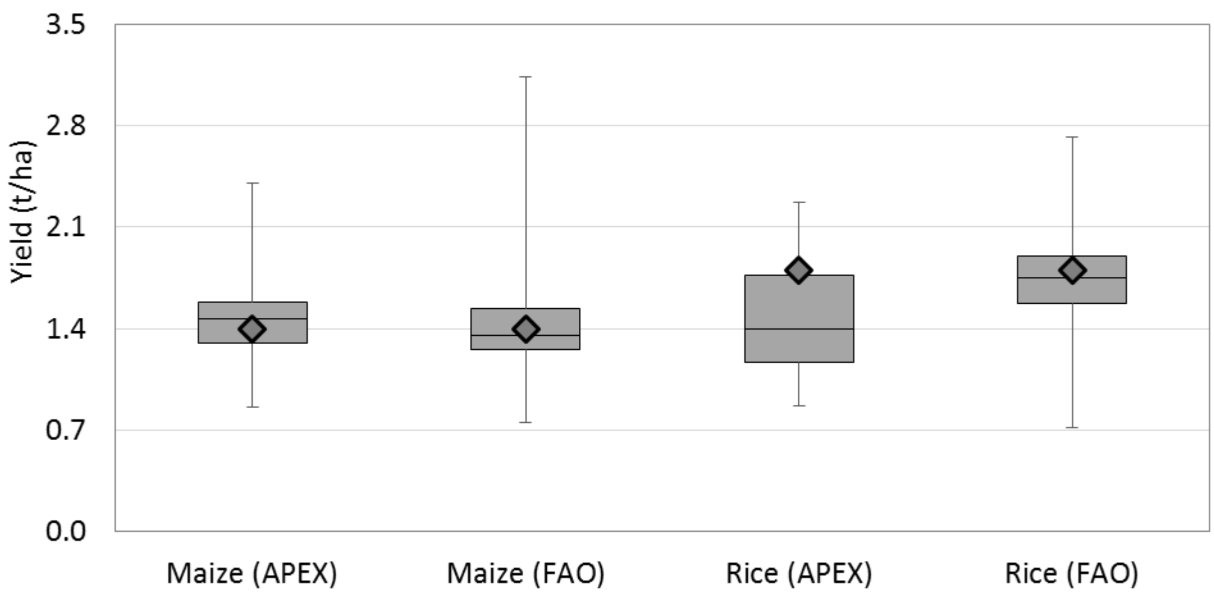


Figure 7: Comparison of APEX vs. FAOSTAT Maize yield from 1981 to 2010, SPAM crop yield in diamond for year 2005.

4.2 Hydrology. For Tanzanian sites, our field research and expert opinion suggested that farmers are diverting stream flows for SSI purposes. Therefore, this study uses stream flows, composed of surface runoff, shallow lateral subsurface flows, and deeper return flows, for irrigating crops during the dry season. The proposed SSI interventions simulated with SWAT (denoted below as the "SSI (ex ante) scenario" were:

i. on agricultural land with slopes less than 8% (7,030 ha): cultivation of rice in the rainy season, coupled with cultivation of irrigated rice in the dry season (repeated irrigation with 50 mm of irrigation water, diverted from nearby streams, during months with insufficient rainfall, and applied whenever insufficient soil moisture stressed crop growth by 25%);

ii. on agricultural land with slopes greater than 8% (960 ha): cultivation of maize in the rainy season with baseline fertilizer; coupled with cultivation of irrigated tomato in the dry season (irrigated when water stress was equal to 25%); and

iii. on agricultural land with slopes of greater than 8% (960 ha): cultivation of maize in the rainy season, fertilized at improved rates (50 kg/ha of urea, in split applications, and 50 kg/ha of DAP); coupled with cultivation of irrigated tomato in the dry season (irrigated when water stress was equal to 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, are set forth in Appendix A1.

4.2.1 Water resources potential. The spatial distributions of the annual groundwater and surface water resources in the Mkindo watershed are presented in figure 8. Groundwater and surface water resources were higher at the top of the mountain and in the low land. The sloping lands between the high and low elevations had little groundwater recharge. The upper part of the watershed consisted of forested land with high evaporation rates (due to canopy storage) and high infiltration, resulting in low surface runoff in this area of the watershed.

The simulated average annual groundwater recharge varied from 10 mm to 168 mm, and annual surface runoff ranged from 22 mm to 108 mm (fig. 8). For the Mkindo watershed, with a catchment area of 32,131.5 ha, the average annual volumetric groundwater recharge and surface runoff were over 18 million m^3 and 15.8 million m^3, respectively.

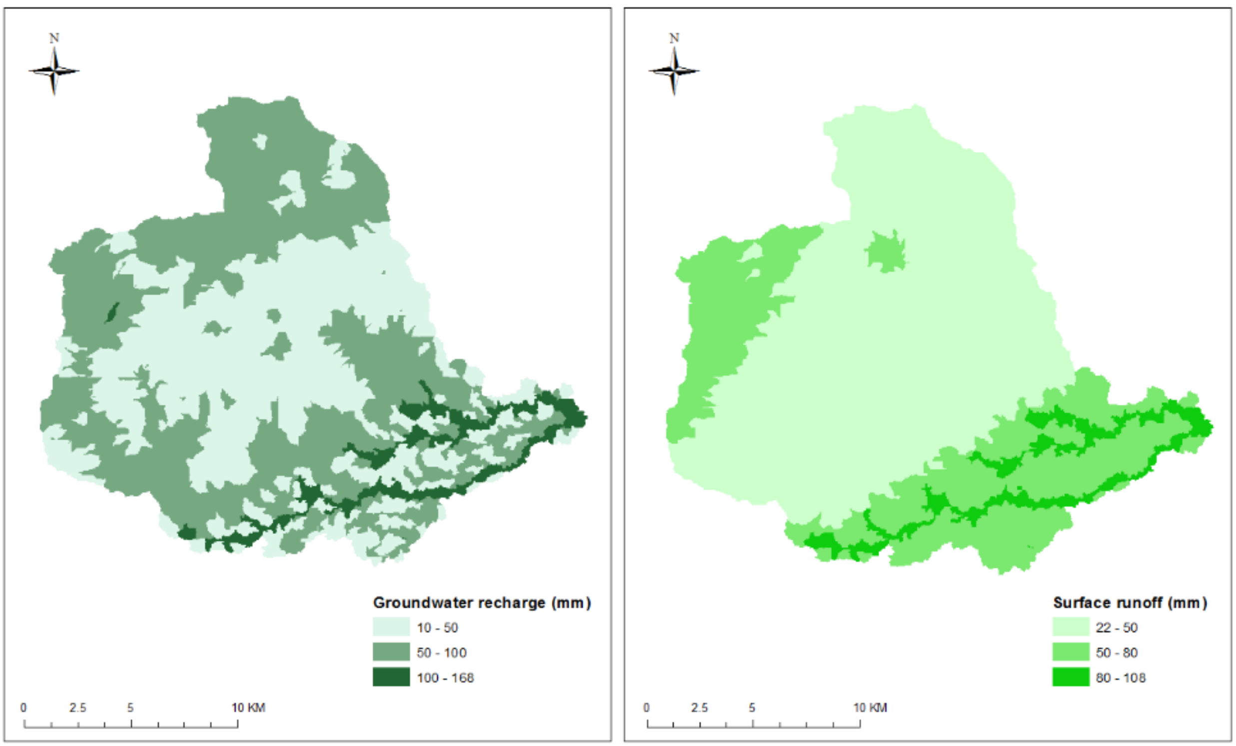


Figure 8. Water resources potential in the Mkindo watershed: a) average annual groundwater recharge; and b) surface runoff.

4.2.2 Watershed water balance impacts of the SSI (ex-ante) scenario. The average annual rainfall in the Mkindo watershed for the period from 1980 to 2010 was 688 mm. Streamflow was about 16% of annual rainfall, and 82% of rainfall evaporated back into the atmosphere (fig. 9). Evaporation rates in the watershed were high because of the substantial percentages of forest and shrub land in the watershed (and associated canopy storage) and because of water ponding in the rice fields. Base flow contributed 63% of stream flow in the watershed, and surface runoff contributed 37%.

Implementation of irrigated, dry-season rice and tomato production did not affect overall water balance dynamics in the watershed, because the irrigated area comprised just 24.87% (7,990 ha) of the entire watershed.

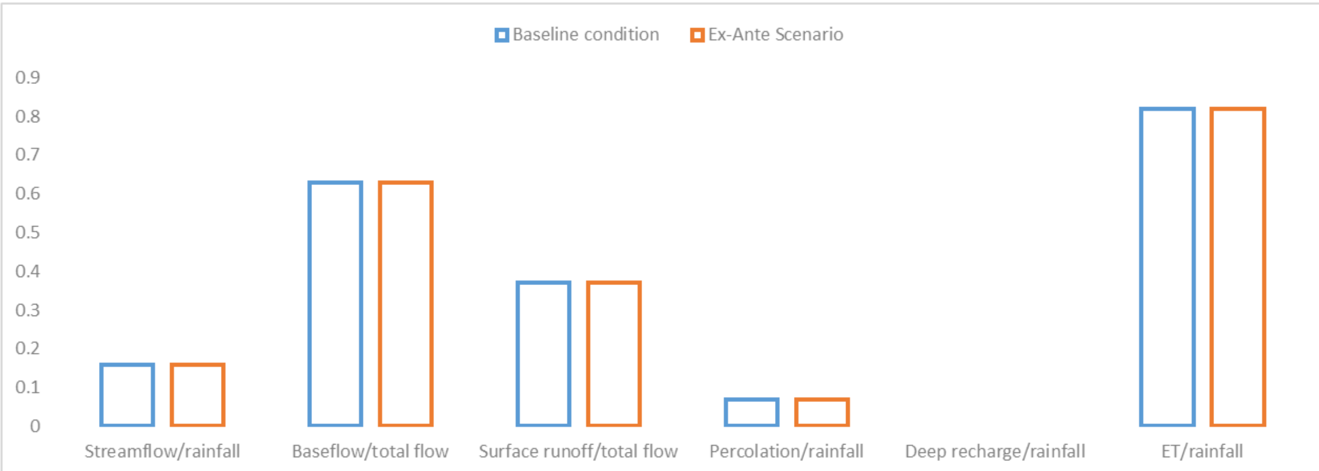


Figure 9. Water balance partitioning for the Mkindo watershed in the baseline scenario and irrigated rice/tomato (SSI, ex ante) scenario.

4.2.3. Applied irrigation. Figure 10 illustrates the average annual irrigation volumes (in m^3) applied for production of dry-season, irrigated rice and tomato crops where: (a) rainy-season crops are fertilized at baseline rates, and b) the rainy-season maize crop is fertilized at improved fertilizer rates. The amount of irrigation water is presented in volumetric terms at the subbasin scale. Thus, the volume of irrigation water 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.

Much of the watershed was forestland or shrub land and irrigation was not practiced. On irrigated fields, spatio-temporal annual irrigation amounts ranged from 1.5 mm to 305 mm, depending on location of the field within the watershed and the climatic year (fig. 10). Most irrigated fields were close to the rivers, since the source of irrigation water was traditional river diversion.

Where rainy-season crops were fertilized at baseline rates (fig. 10a), the average annual volume of irrigation water withdrawn per subbasin ranged from 37 m^3 to 204,768 m^3. The total annual volume of irrigation water withdrawn was 5,827,425 m^3, or approximately 14% of the annual stream flow leaving the watershed. Irrigation amounts across the subbasins did not differ significantly when the rainy-season maize crop was fertilized at improved fertilizer rates (fig. 10b).

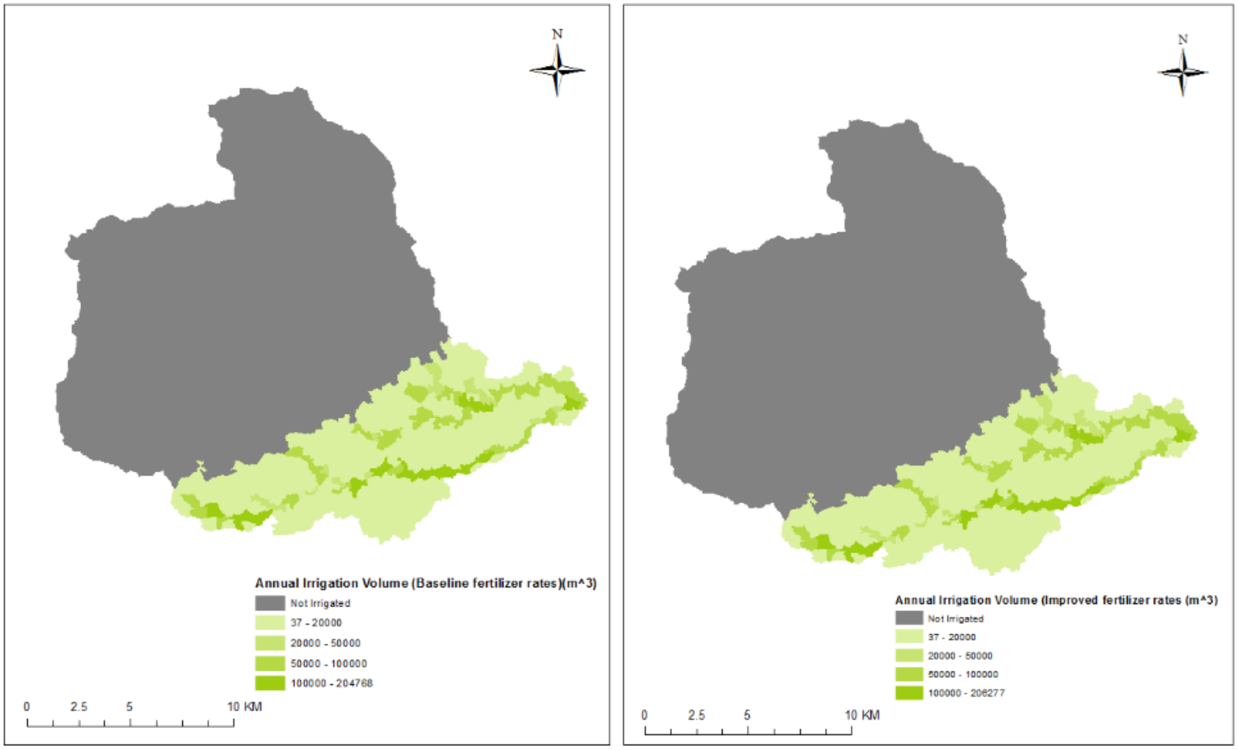


Figure 10. Average annual irrigation volumes (in m^3) for dry-season, irrigated rice and tomato crops where: a) rainy season crops are fertilized at baseline fertilizer rates, and b) the rainy-season maize crop is fertilized at improved fertilizer rates.

4.2.4 Changes in stream flows. Implementation of the proposed SSI interventions resulted in a slight reduction in the average stream flow at the outlet of the Mkindo watershed. In the baseline scenario, the average monthly stream flow from 1980 to 2010 was 1.31 m^3/sec; the proposed SSI interventions reduced the average monthly stream flow by only 3%, to 1.27 m^3/sec. The average monthly stream flows varied only slightly when the rainy-season maize crop was fertilized at improved, rather than baseline, rates. Minor reductions were observed with the recession limb of the hydrographs with the implementation of the proposed SSI interventions (fig. 11). These results suggest that implementation of the proposed SSI interventions would not compromise downstream flows.

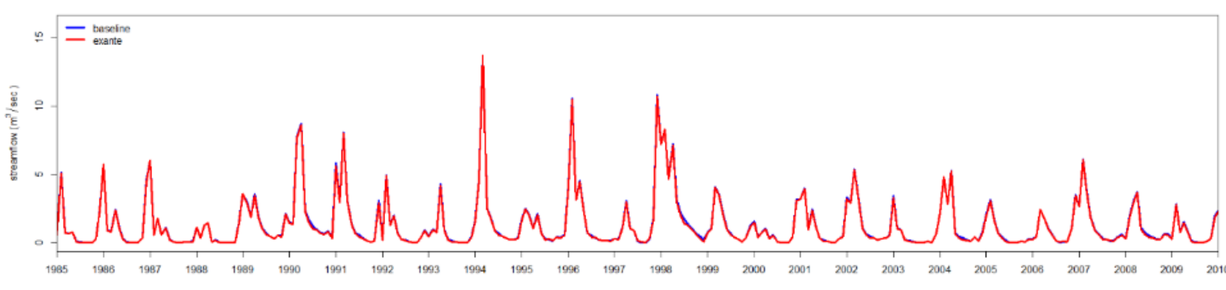


Figure 11. Stream flow at the outlet of the Mkindo watershed for the baseline scenario and SSI (ex ante) rice/tomato scenario.

The flow duration curve also indicates that the implementation of expanded SSI will slightly reduce monthly stream flows (fig. 12). For example, the monthly stream flow at 50% probability of exceedance was reduced by only 1.34%; at 80% probability of exceedance, monthly stream flow was reduced by 2.93%. Changes in stream flow were not observed at the high and low flows with withdrawals for water harvesting.

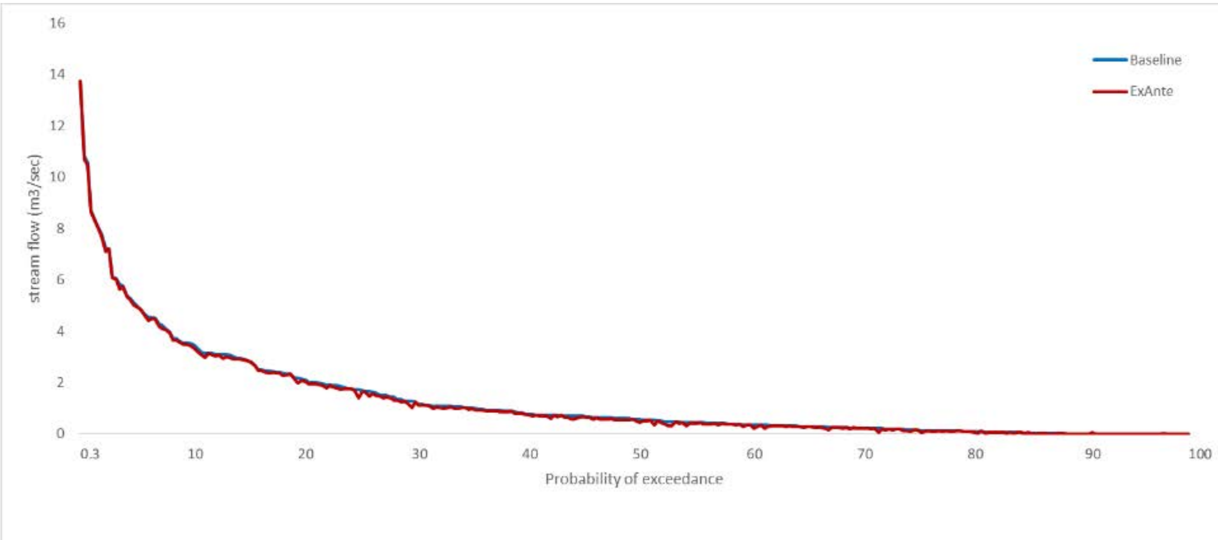


Figure 12. Flow duration curve for the monthly stream flow in the baseline scenario and irrigated rice/tomato scenario.

Although simulations indicated that there is ample water available for SSI in the Mkindo watershed, and that the proposed SSI interventions would not compromise the environmental health of the watershed, there is little currently uncultivated agricultural land (with slopes less than 8%) available for cultivation close to rivers in the Mkindo watershed. Suitable cultivated fields that were close to rivers received sufficient amounts of water for irrigation, but those suitable fields that were far from rivers received less irrigation. Significant expansion of proposed SSI interventions will therefore require development of advanced surface water diversion and transfer technologies and/or wells to irrigate fields located far from the rivers.

4.3 Alternate scenarios simulated with APEX. The analyses that follow reference APEX baseline and alternative scenarios 1-4, summarized above. The baseline and four alternative scenarios simulated by APEX are specifically defined as follows:

Baseline: Maize and rain-fed rice are grown in the wet season. Tomatoes, cabbage, fodder (vetch/oats) and Napier grass are grown on very limited land with minimal or no irrigation. Fertilization is also minimal.

Alternative scenario 1: multiple cropping of rain-fed, unfertilized grain crops (rain-fed rice and maize) in the rainy season with irrigated crops (i.e., cabbage, tomato, and oats/vetch) in the dry season.

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 (i.e., cabbage, tomato, oats/vetch) in the dry season.

Alternative scenario 3: cultivation of alfalfa and Napier grass as perennial crops.

Alternate scenario 4: continuous cropping of irrigated SRI rice, following two alternate irrigation schedules: a 3-day wetting period followed by a 5- day drying period; and a 3-day wetting period followed by a 7-days drying period.

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 fodder, cabbage and tomato. Simulations indicated a significant difference between yields of maize grown as a continuous crop and as a multiple crop with fodder and tomato, with a p-value of less than 0.05. Multiple cropping of maize with fodder (as opposed to continuous cropping of maize) decreased the nitrogen stress days by 22% and consequently increased maize yield by 33%, whereas multiple cropping of maize with tomato increased the nitrogen stress days by 12% and consequently decreased maize yield by 40%. The simulation did not show any significant difference between yields of continuously cropped maize and maize grown as a multiple crop with cabbage. The simulation indicated that fodder (vetch + oats) enriched soil nitrogen and consequently increased the subsequent maize yield, while tomato reduced soil nitrogen for the succeeding crop and consequently reduced maize yield.

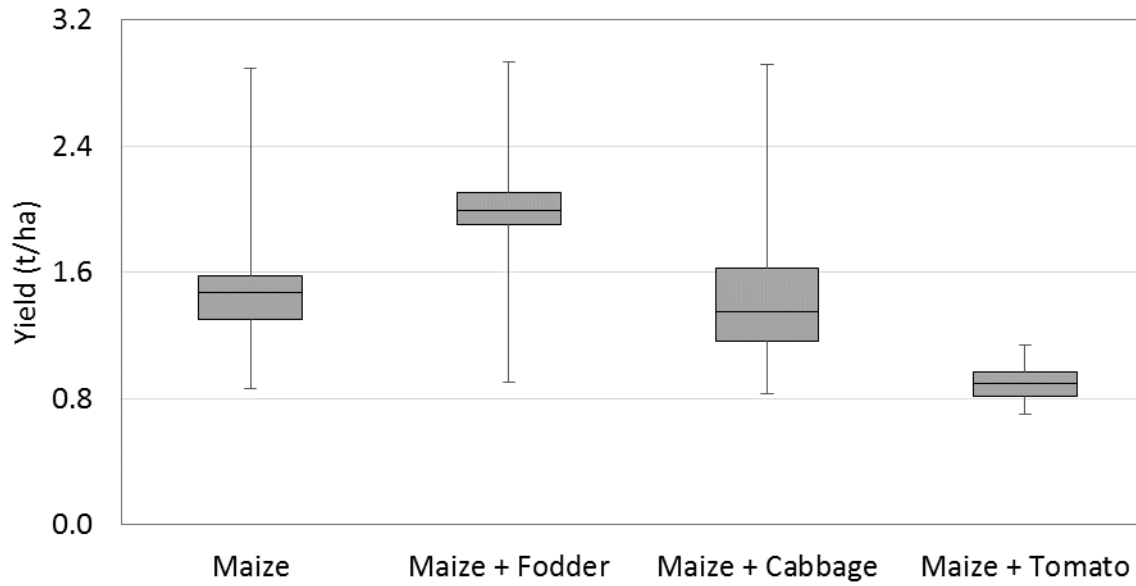


Figure 13. Maize yields when continuously cropped and when grown as a multiple crop with fodder, cabbage and tomato (from 1981 to 2010). In this figure and all of the figures included in Section 4.3, the rectangle box represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

Figure 14 shows the simulated yields of rain-fed rice when continuously cropped and when grown as a multiple crop with fodder, cabbage and tomato. The simulation did not show a significant difference in yields when rice was grown as a multiple crop with cabbage, fodder and tomato (as compared to continuously cropped rice yield).

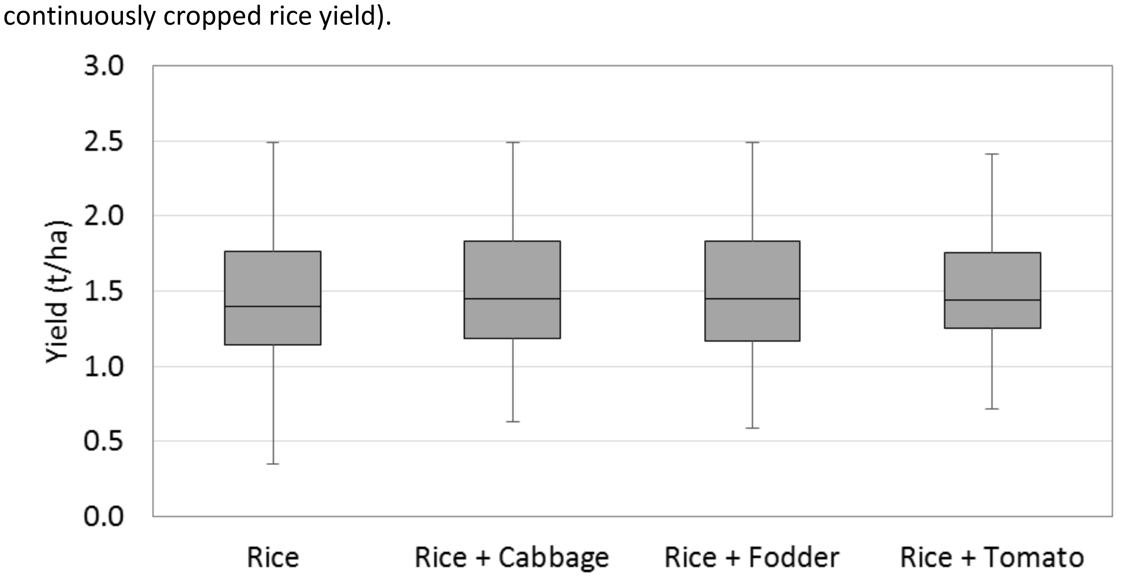


Figure 14. Yields of rain-fed rice when continuously cropped and when grown as a multiple crop with fodder, cabbage and tomato (1981 to 2010).

The results of dry-season, irrigated, alternative crops, simulated as continuous crops and as multiple crops with rain-fed rice and maize, are shown in figures 15, 16, and 17. As compared to the yield of continuously cropped tomato, tomato yield was limited by nitrogen fertility. Nitrogen stress days increased when tomato was planted with maize by 24% and reduced by 12% when planted with rice. Consequently tomato yield increased 12% when grown as a multiple crop with rice, and decreased by 38% when grown as a multiple crop with maize (fig. 15). Cabbage and fodder yields were consistent across continuous cropping and multiple cropping systems (fig. 16 and fig. 17).

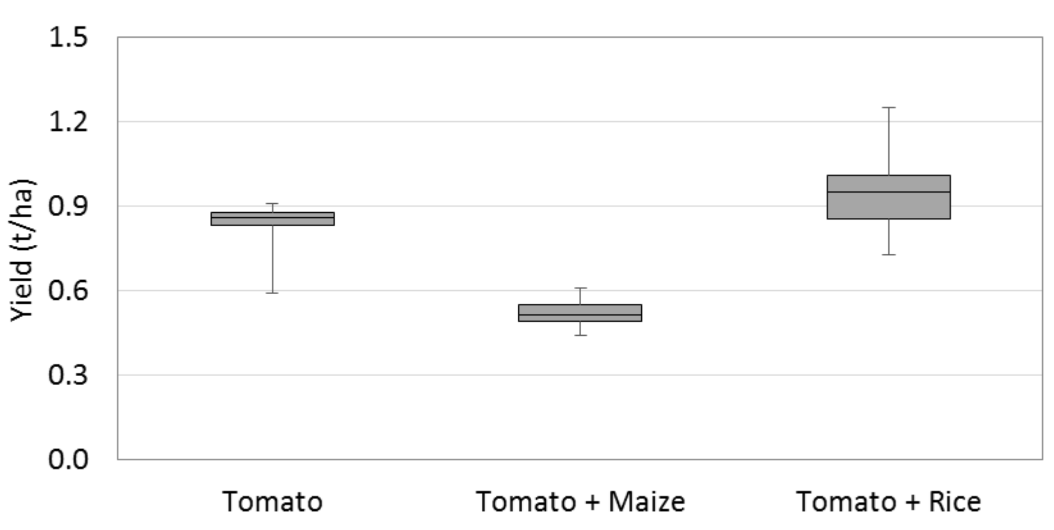


Figure 15. Tomato yield when continuously cropped, and when grown as a multiple crop with maize (with and without fertilizer) and with rain-fed rice (1981 to 2010)

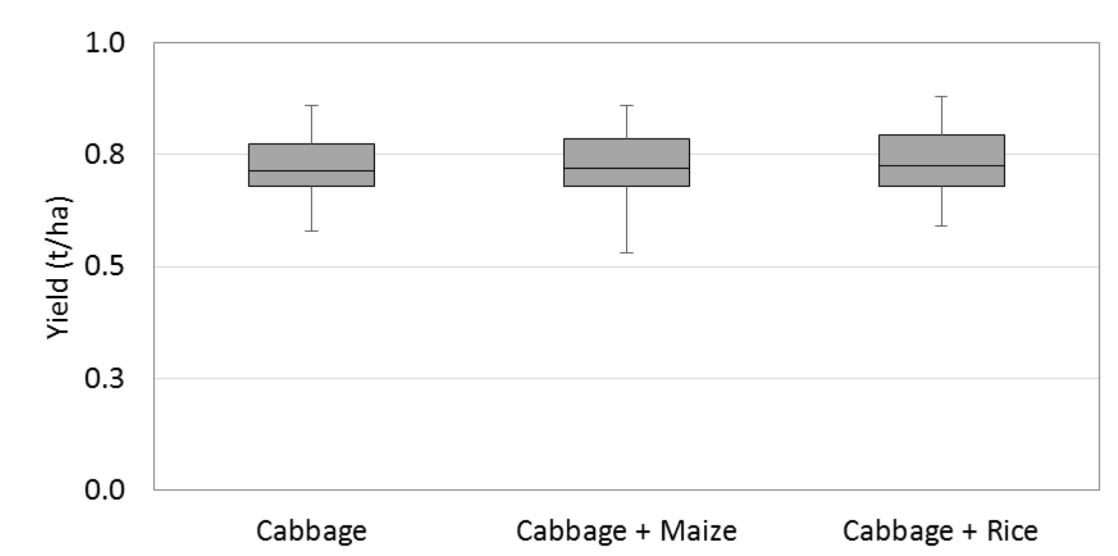


Figure 16. Cabbage yield when continuously cropped, and when grown as a multiple crop with maize (with and without fertilizer) and with rain-fed rice (1981 to 2010)

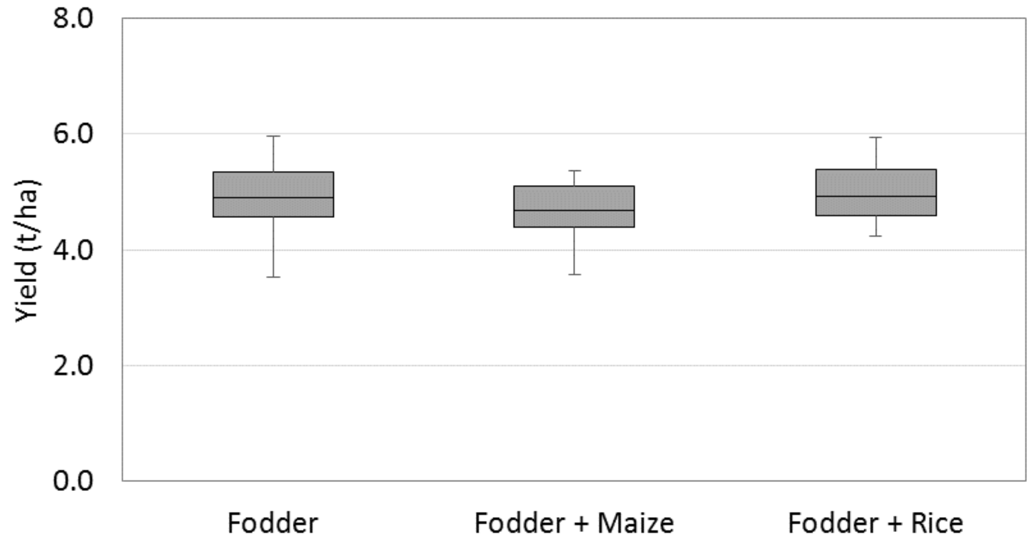


Figure 17. Fodder yield when continuously cropped, and when grown as a multiple crop with maize and rain-fed rice (1981 to 2010)

Alternative scenario 2. In alternative scenario 2 we simulated 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 cabbage, tomato, and fodder. The results of the simulation are depicted in figure 18. Addition of the fertilizer decreased the number of nitrogen stress days by 52% to 30 days and increased the yield of continuously cropped maize by approximately 95% (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. Simulations of multiple cropping systems indicated significant differences in yields when fertilized maize was grown as a multiple crop with fodder and tomato. Double cropping of fodder with fertilized maize further decreased the number of nitrogen stress days to 14, while double cropping of fodder with tomato increased to the number of nitrogen stress days to 35. As compared to the continuously cropped, fertilized maize yield, fertilized maize yield increased by 22% when planted after fodder, but decreased by 32% when planted after tomato (fig. 18). Multiple cropping of fertilized maize with cabbage did not significantly affect the fertilized maize yield (fig. 18).

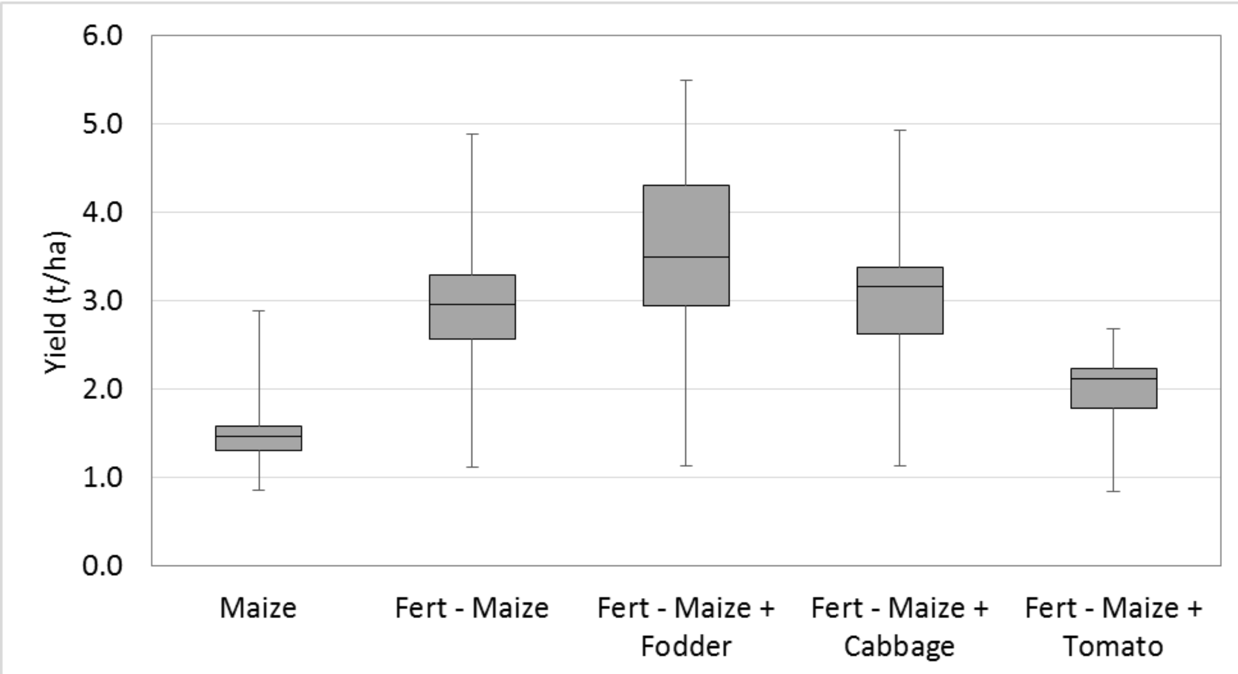


Figure 18. Continuously cropped, unfertilized maize yield, compared with yields of continuously cropped, fertilized maize, and fertilized maize grown in a multiple cropping system (1981 to 2010).

Alternative scenario 3. In alternative scenario 3, alfalfa and Napier grass were planted and managed as irrigated perennial crops. The first alfalfa harvest was scheduled after 6 months, with a subsequent cutting every 60 days over 5 years before the crop was replanted. The first Napier grass harvest was scheduled 3 months after planting, followed by cutting every 60 days for 3 years before replanting. Figure 19 shows the forage yields (t/ha) for alfalfa and Napier grass. Irrigation was applied to fill the root zone soil moisture to field capacity, and a maximum annual irrigation volume of 800 mm was budgeted. Napier yield was limited by nitrogen temperature and water stress. On average, Napier was stressed for 60, 36 and 5 days per year for nitrogen, water and temperature, respectively. Alfalfa was stressed only for water, for an average of 87 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).

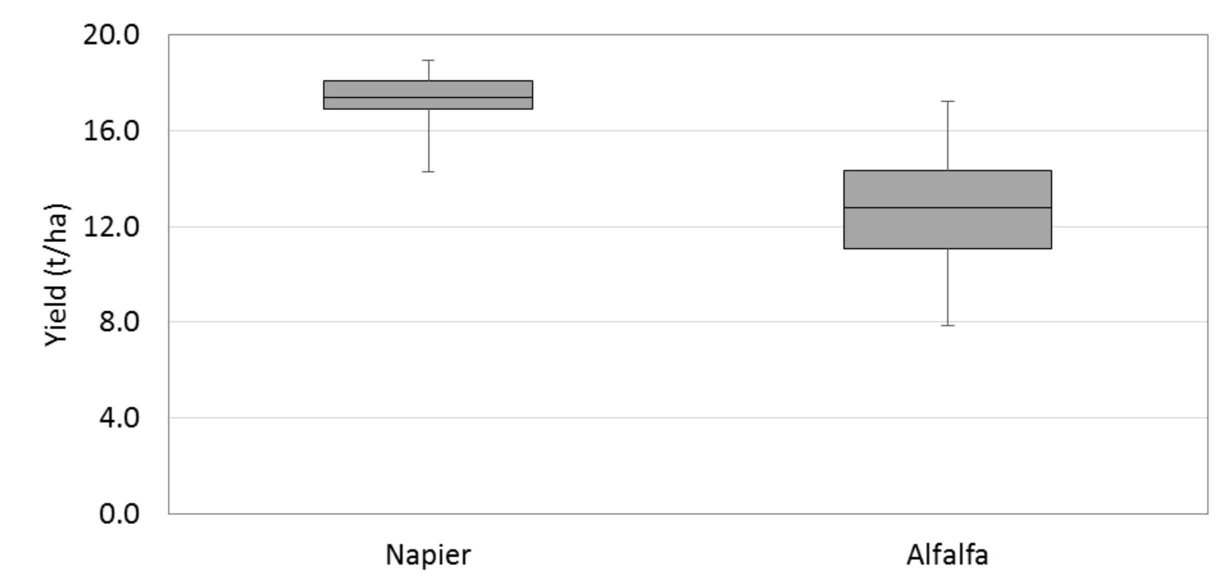


Figure 19. Yields of Napier grass and Alfalfa as perennial crops (1981 to 2010)

Alternate scenario 4. In alternative scenario 4, SRI rice was simulated by varying the drying days from 5 to 7 while wetting (flooding the paddies) for 3 days. The fields were flooded with 15 mm of water in the wetting periods, and then the dikes were destroyed to drain the fields. The procedure was repeated after 5 and 7 drying days until 2 weeks before harvest. The 7-day drying period used 20% less water than the 5-day drying period, but the number of water stress days with a 7-day drying period (as compared to the 5-day drying period) increased by 150%; consequently, the 7-day drying period resulted in a 53% reduction in crop yield (fig. 20).

Figure 20. SRI rice yield simulation for 3 days wetting and 5 and 7 days drying (1981 to 2010)

4.3.2 Runoff and sediment yields

Alternative scenarios 1 and 2. The effects of alternative scenarios 1 and 2 on flow and sediment losses are shown in figures 21 and 22, respectively. For dry-season crops, irrigation was applied to fill the root zone soil moisture to field capacity. Dry-season tomato and cabbage were planted at the end of April and fodder was planted in June; therefore, there was limited cover crop on the ground in May, when the watershed receives approximately 13% of the annual rainfall and the soil is already saturated from the long rainy season. Accordingly, double cropping scenarios resulted in increases in simulated runoff. In scenario 1, as compared to the baseline (rain-fed maize) scenario, runoff increased significantly when maize was planted as a multiple crop with tomato at a p-value of less than 0.05. Multiple cropping of maize with cabbage did not produce significant changes in runoff. In scenario 2, continuous cropping of fertilized maize and multiple cropping of fertilized maize with tomato, fodder and cabbage increased runoff significantly; the largest runoff increase was observed with multiple cropping of fertilized maize and tomato (49%), and a smaller runoff increase was observed with multiple cropping of fertilized maize and cabbage (22%).

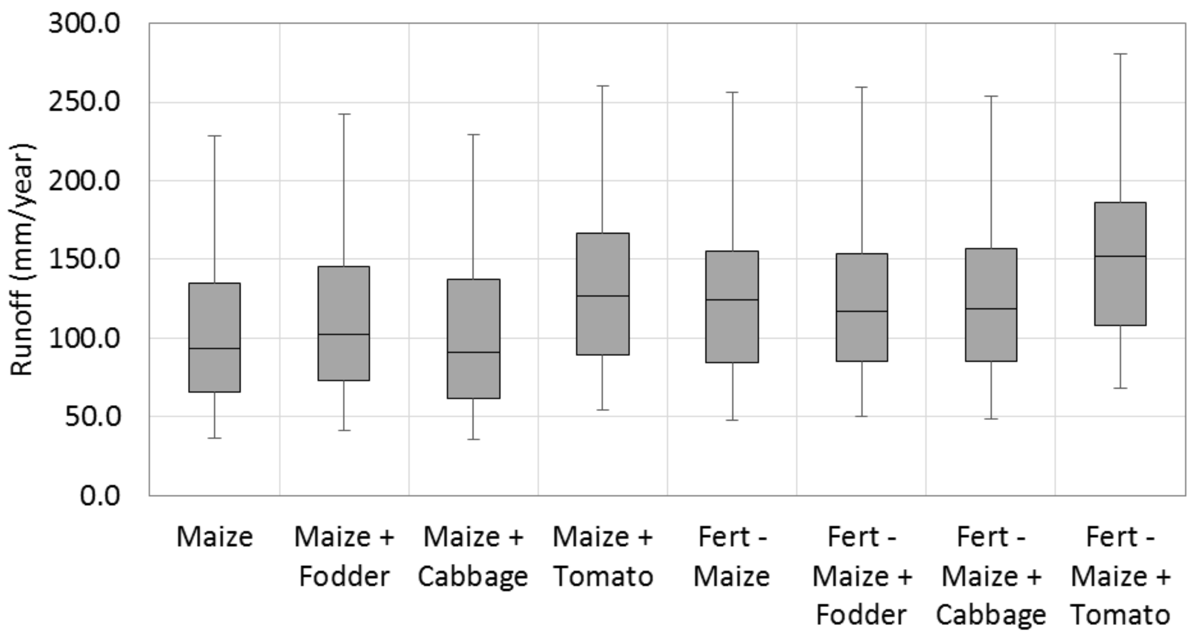


Figure 21. Runoff yields in alternative scenarios 1 and 2

The effects of alternative scenarios 1 and 2 on sediment yields are plotted in figure 22. Sediment yields for the baseline period from 1981 to 2010 ranged from 6 to 45 t/ha. Generally the simulation indicated that the application of nitrogen fertilizer in the rainfed maize season would improve the leaf area and biomass of the traditional and irrigated crops; as a result, the soil would be protected from direct exposure to rainfall erosivity and erosion would be reduced. Multiple cropping of rain-fed, unfertilized maize with fodder, cabbage and tomato in did not significantly change sediment yields compared with the baseline scenario; however, continuous cropping of fertilized maize and multiple cropping of fertilized maize with fodder, cabbage, and tomato reduced sediment yield by approximately 25%, 32%, 24%, and 35%, respectively.

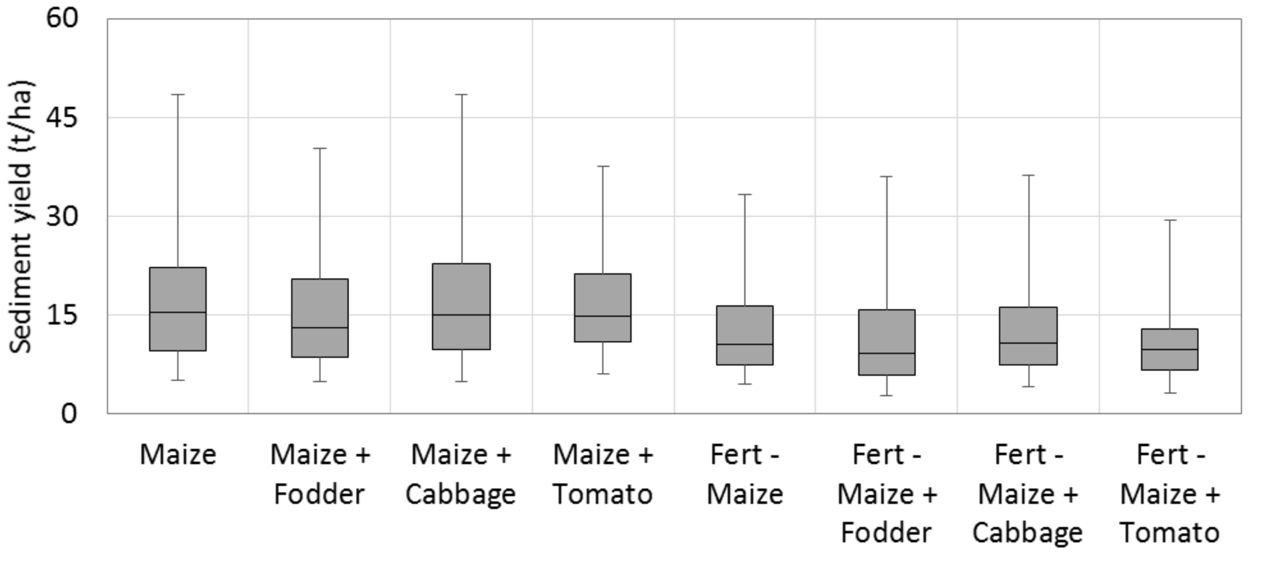


Figure 22. Sediment yields of alternative scenario 1 and 2

Alternative scenarios 3 and 4. APEX simulations indicated that continuous cropping of alfalfa and Napier grass would reduce soil erosion by 85% and 98%, respectively, compared with the baseline scenario. Simulations indicated that alfalfa would reduce runoff by 26% compared to the baseline crop of continuously planted maize, but that Napier grass would not reduce the runoff yield significantly at a p-value of less than 0.05. Continuous cropping of SRI Rice simulated for 5 and 7 drying days reduced both soil and runoff losses significantly compared to the baseline, since the dikes were constructed on the perimeter of the rice fields, and the amount of water applied in the wetting period (15mm) was close to evapotranspiration requirements.

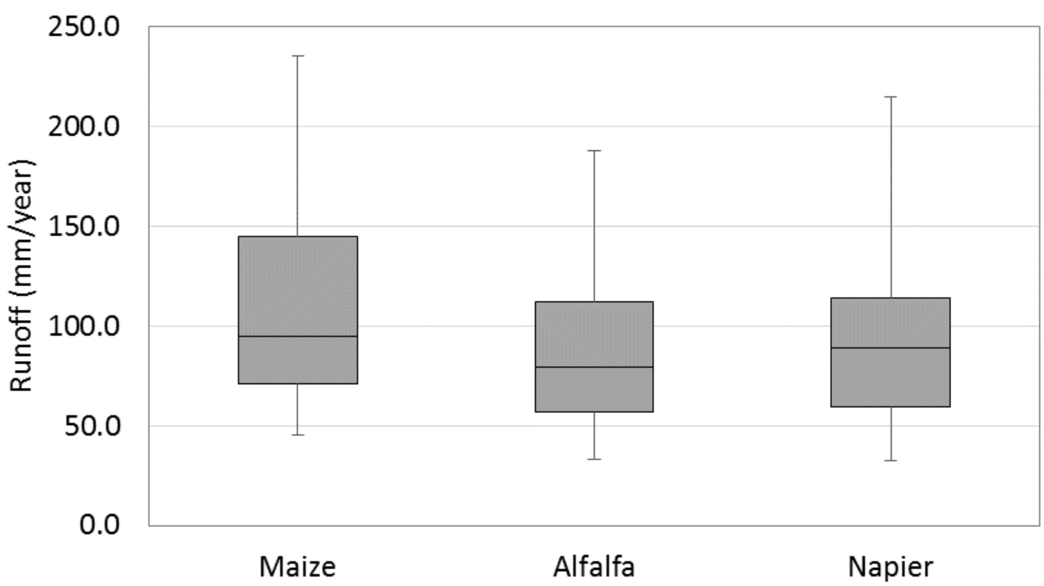


Figure 23. Runoff yields of alternative scenario 3 compared with baseline scenario

4.4 Economic analyses. The analyses that follow reference the baseline scenario and FARMSIM alternative scenarios 1-3, discussed in some detail above. The baseline scenario and three alternative scenarios are specifically defined as follows:

> Baseline (current fertilizer + no irrigation + rain-fed rice): Maize and rain-fed rice are grown in the wet season. Tomatoes, cabbage, fodder (vetch/oats) and Napier grass are grown on very limited land with minimal or no irrigation. Fertilization is also minimal.
>
> Alt. 1 (irrigated vegetables/fodder + recommended fertilizers + rain-fed rice): Irrigable land is allocated (according to the slope of the fields) to rain-fed rice and fertilized maize in the rainy season. On areas allocated to fertilized maize in the rainy season, irrigated vegetable and fodder crops (cabbage, tomato, and oats/vetch) are grown during the dry season.
>
> Alt. 2 (irrigated vegetables/fodder + recommended fertilizers + SRI rice):): Irrigable land is allocated (according to the slope of the fields) to rain-fed rice and fertilized maize in the rainy season. On areas allocated to fertilized maize in the rainy season, irrigated vegetable and fodder crops (cabbage, tomato, and oats/vetch) are grown during the dry season. On areas allocated to rain-fed rice in the rainy season, SRI rice is grown during the dry season following a strict protocol specifying a 3-day wetting period followed by a 5-day drying period.
>
> Alt. 3 (irrigated vegetables (no fodder) + recommended fertilizers + SRI rice): Same as FARMSIM Alt. 2, above, except only tomato and cabbage (and not oats/vetch) are cultivated as irrigated, dry-season crops in areas allocated to fertilized maize in the rainy season.

Note that our evaluation did not include the capital costs of developing advanced surface water diversion and transfer technologies such as using pumps and/or wells to sufficiently irrigate fields located far from the rivers, as the technologies required and associated costs are subjects for future studies. In addition, costs associated with large irrigation infrastructure such as dams and canals were not taken into account, as those costs are best captured at a macroeconomic level. On average, costs of irrigation infrastructure in Sub-Saharan Africa can be as high as US$5000/ha (Inocencio et al. 2007, p.18). An irrigation scheme of 60 ha, such as that of Mkindo, can therefore cost up to US$300,000 or 630,000,000 TZS.

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 Tanzania, we used information collected on the ILSSI-Ethiopia case study.

The farm-level simulation results for the four 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. The NPV results, as illustrated by the cumulative distribution function (CDF) graph in figure 24a, clearly indicate the importance of investing in irrigation and fertilizers. The adoption of the SRI system for rice cultivation and the use of increased fertilizers on the maize crop, in combination with maximal irrigation (Alts. 2 and 3) result in a significant increase in NPV at all levels of risk. In fact, their CDF values lie completely to the right of the other scenarios for all 500 draws of the model, indicating total preference for these scenarios by all risk-averse decision makers. Allocation of all irrigable land to vegetable crops during the dry season (Alt. 3) is preferable to mixed vegetable and fodder production (Alt. 2) for all 500 draws of the model. Cultivation of rain-fed rice in combination with increased fertilization and maximal irrigation (Alt. 1) perform better than the baseline scenario.

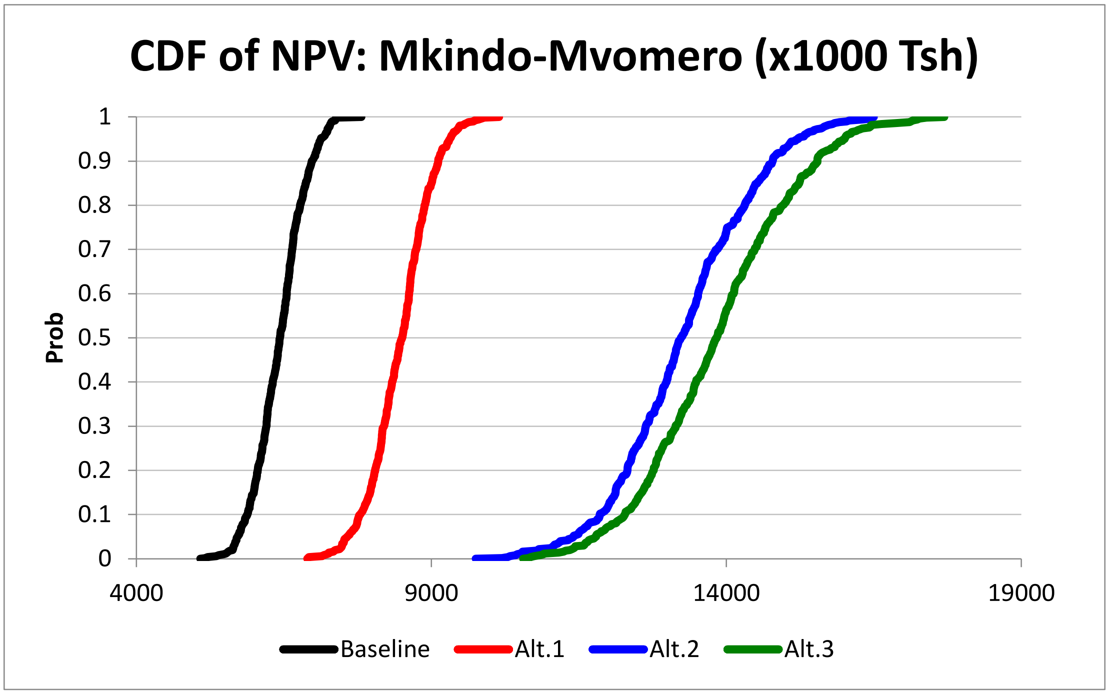


Figure 24a. Cumulative distribution function of NPV for Mkindo village

The stoplight chart below shows the probabilities in each of the four scenarios of NPV being less than 6,400,000 TSh (Tanzanian Shillings) (red), greater than 13,500,000 TSh (green), or between the two target values (yellow). The target values are respectively the NPV averages of the baseline scenario for the lower bound and the best performing alternative scenarios (Alt. 2 & 3) for the upper bound. In the baseline scenario, there is a 47% chance that NPV will be less than 6,400,000 TSh, and a 0% chance that NPV will exceed 13,500,000 TSh. In contrast, a farmer who adopts the SRI system and increases irrigation and fertilization (Alts. 2 and 3) has a 41% and 59% chance, respectively, of generating NPV greater than 13,500,000 TSh; in both these scenarios, there is a 0% chance that NPV will be less than 6,400,000 TSh. Note that, as in the CDF graph, the scenario involving the reallocation of fodder acreage to vegetable production (Alt. 3) generates the highest NPV.

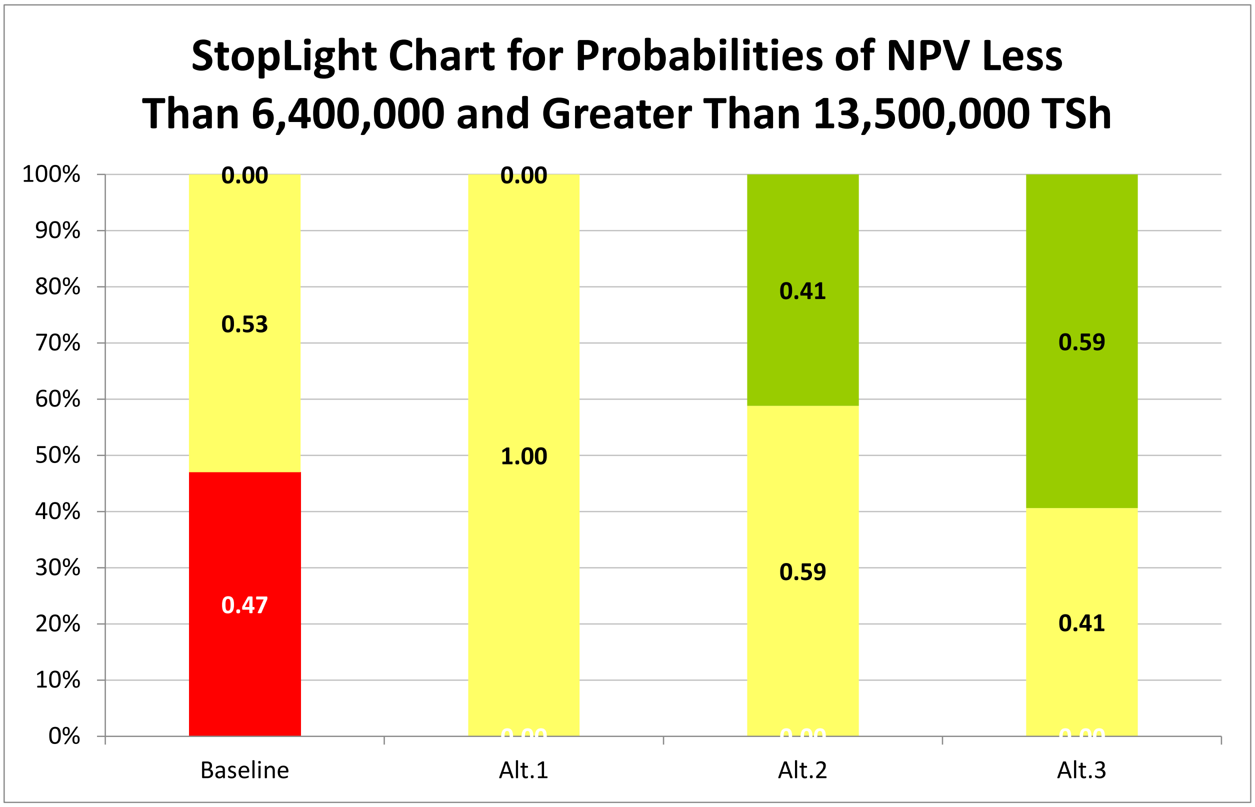


Figure 24b. StopLight chart of NPV for Mkindo village

4.4.2 NCFI. The CDF graph for annual NCFI (fig. 25a) indicates that the adoption of the SRI system, combined with increased fertilizers and irrigation (Alts. 2 and 3), are preferred scenarios, as their CDF values lie completely to the right of the other scenarios for all 500 draws of the model. Rain-fed rice production combined with increased irrigation and fertilizers (Alt. 1) performed only slightly better than the baseline scenario.

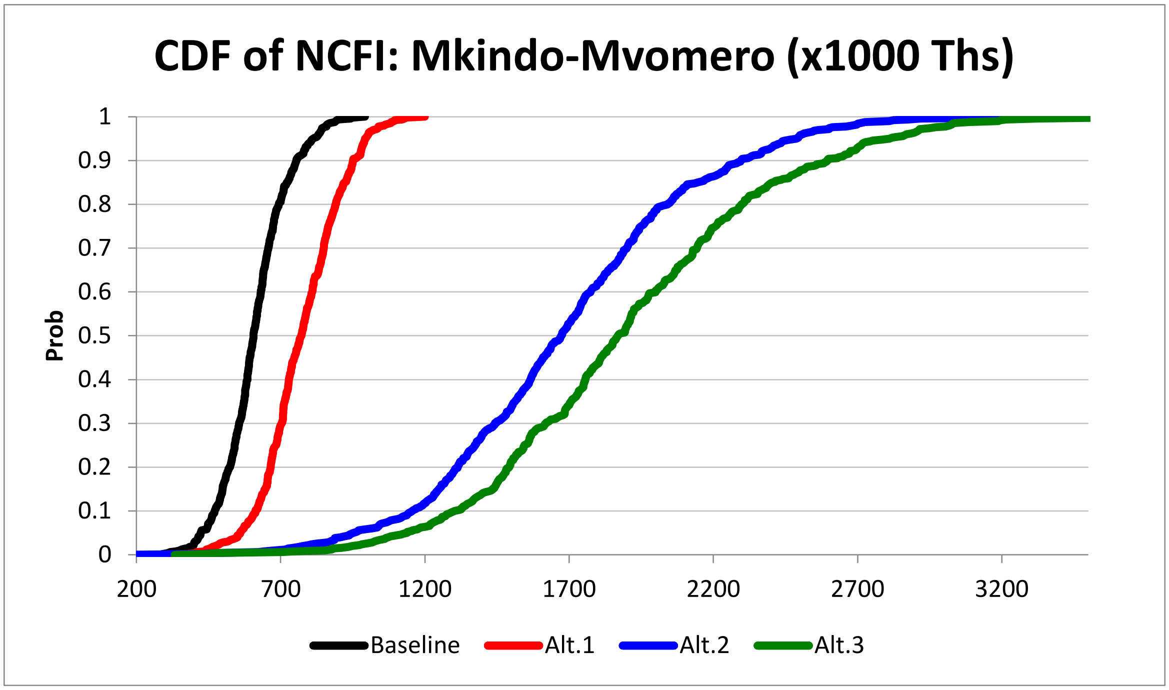


Figure 25a. Cumulative distribution function of the NCFI for Mkindo village

The Stoplight chart in figure 25b illustrates NFCI in year three for the baseline and three alternative scenarios. In the baseline scenario, there is an 80% chance that NCFI will be less than 700,000 TSh and a 0% chance that NCFI will exceed 1,800,000 TSh. In contrast, farmers that adopt the SRI system and increased irrigation and fertilization (Alts. 2 and 3) have only a 1% chance of generating NCFI of less than 700,000 TSh; a farmer that cultivates both vegetables and fodder (Alt. 2) has a 38% chance of NCFI exceeding 1,800,000 TSh, and a farmer that allocates all irrigated land to vegetables (Alt.3) has a 56% probability of NCFI exceeding 1,800,000 TSh.

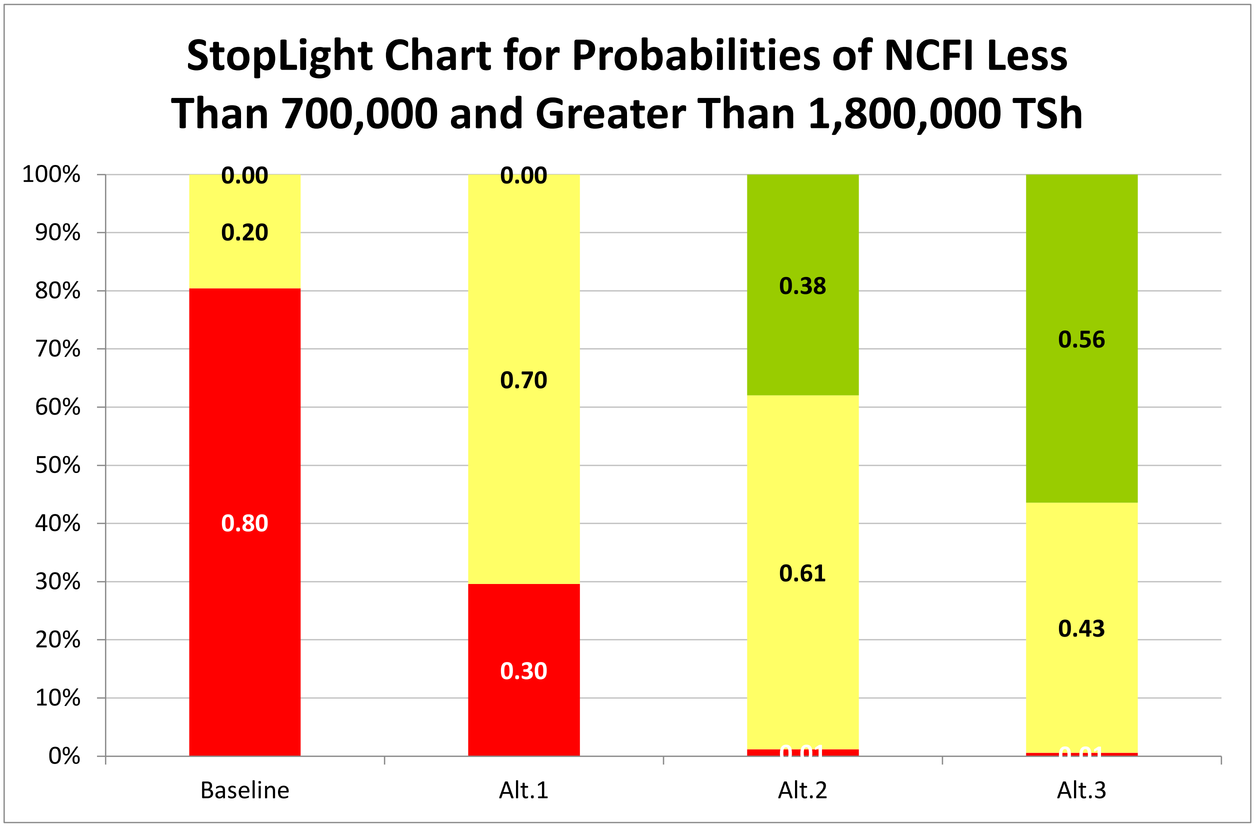


Figure 25b. StopLight chart of the NCFI for Mkindo village

4.4.3 EC. Figure 26a illustrates potential EC in the fifth year of the five-year planning horizon. Once again, the scenarios adopting SRI methods and increased irrigation and fertilization (Alts. 2 and 3) significantly outperform the baseline and rain-fed rice scenario (Alt. 1), in that CDF values for alternative scenarios 2 and 3 lie entirely to the right of CDF values for the baseline and alternative scenario 1. Note that EC in alternative scenario 1 does not differ significantly from the baseline scenario, despite investment in irrigation and fertilizers.

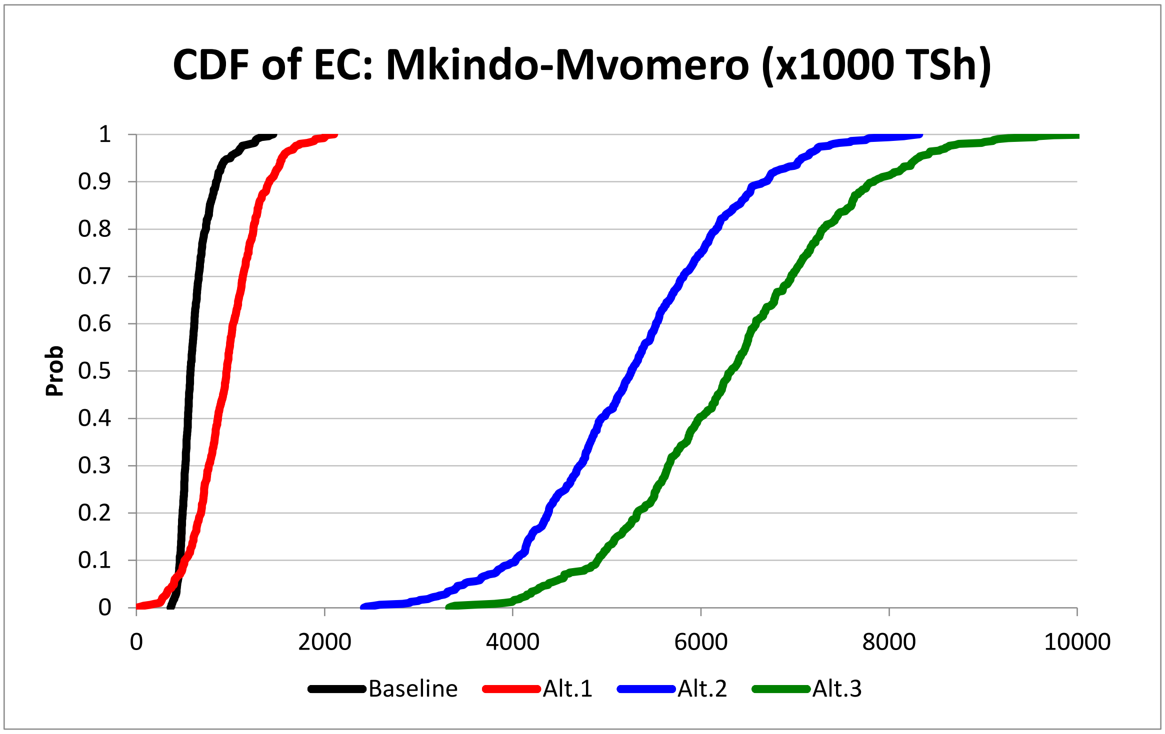


Figure 26a. Cumulative distribution function of the ending cash reserves for Mkindo village

For farmers that apply increased irrigation, fertilizers, and the SRI method for rice cultivation (Alts. 2 and 3), there is a 59% and 87% probability, respectively, that EC in year five will exceed 5,000,000 TSh, and a 0% probability that EC will be less than 700,000 TSh. In contrast, farmers that cultivate rain-fed rice in combination with increased irrigation and fertilizers (Alt. 1) have a 0% chance of generating EC of more than 5,000,000 TSh and a 22% chance of EC of less than 700,000 TSh. For a farmer in the baseline scenario, there is a 77% probability of that EC will be less than 700,000 TSh in year five (fig. 26b).

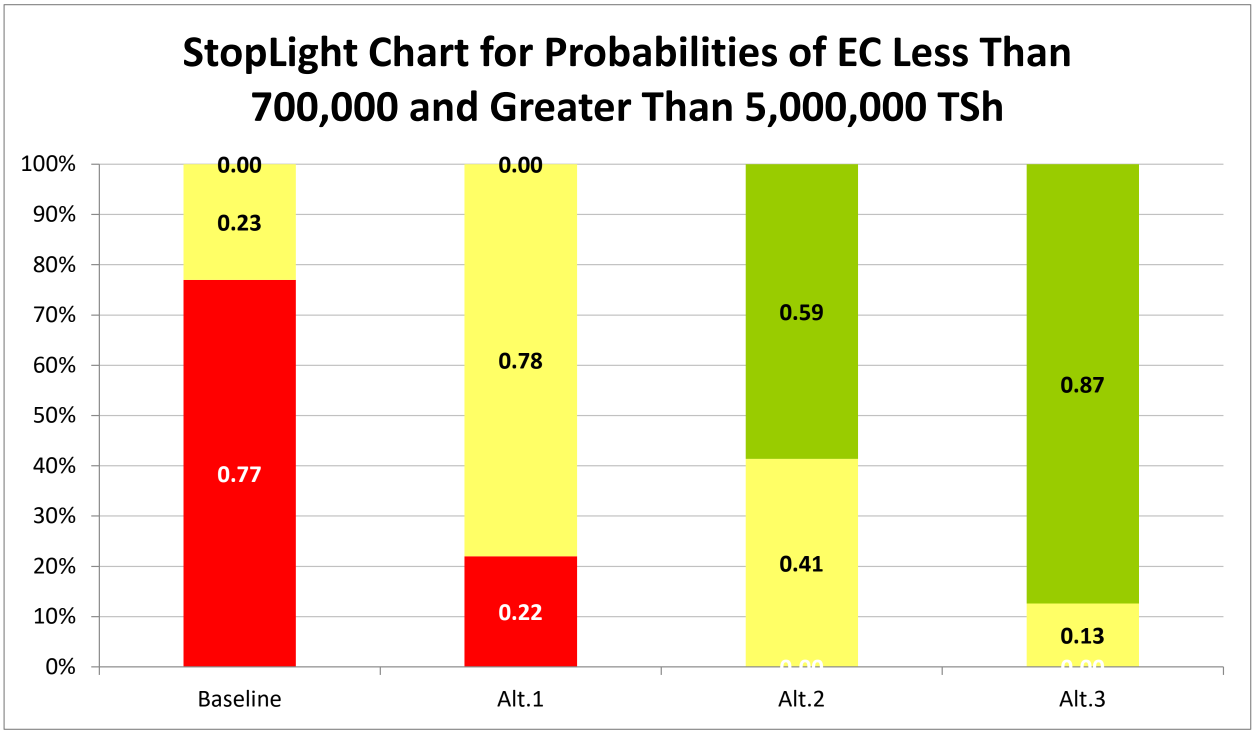


Figure 26b. StopLight chart of the ending cash reserves for Mkindo village

4.4.4 Nutrition. Nutrition is an important component of household well-being. New agricultural technologies that increase crop production may result in improved nutrition; however, the nutritional effects of these new technologies vary according to the type and variety of crops grown and consumed. In our simulations, increased SSI enabled the multiple cropping of dry-season, irrigated crops with rainy-season, rain-fed grain crops, as well as the continuous cropping of SRI rice. This, together with improved fertilization practices, was shown to increase production of rice, maize and vegetables for the families living in Mkindo village, in the Mvomero district in Tanzania.

Simulation results indicate that the quantities of crops consumed by families under the baseline and alternative scenarios provided and even exceeded the levels of calories, proteins and fat required for an adult per day. Levels of calcium and iron showed some improvement (i.e., increase in quantity consumed) in all of the alternative scenarios; however, levels of vitamin A were deficient in the baseline and alternative scenarios.

5. Conclusions

In Mvomero, ILSSI proposed implementing SSI, using diverted river water, to maximize cultivation of high-value vegetable and fodder crops in the dry season and productivity of the rice crop. 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 Mkindo watershed. Agricultural land comprises a relatively small percentage (just 24.86%) of total land in the watershed. Accordingly, the total annual volume of irrigation water withdrawn in the watershed would be less than 5.9 million m^3, or just 14% of the annual stream flow leaving the watershed. Moreover, simulations indicated that proposed SSI interventions would reduce average monthly stream flow by only 3%, and that peak and low flows would not be affected by the withdrawal of irrigation water from rivers. This suggests that the proposed SSI interventions are sustainable, and would not compromise the environmental health of the watershed. Because suitable fields far from rivers receive less irrigation water than those close to rivers, the proposed SSI interventions will require development of advanced surface water diversion and transfer technologies and/or wells to sufficiently irrigate fields located far from the rivers.

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizer would increase crop yields substantially and decrease the soil loss from erosion. 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 if fertilization rates were inadequate. For the fertilizer application scenarios simulated in this study, multiple cropping of maize with tomato increased the nitrogen stress days for both crops and significantly reduced simulated yields of both crops, suggesting that increased fertilization amounts should be considered for multiple cropping of maize with tomato. In contrast, multiple cropping of maize with fodder significantly increased simulated maize yields and did not significantly affect fodder yields.

Simulations also showed that SRI rice production would result in higher crop water productivity compared to traditional rain-fed rice. These results suggest that, as concluded by Worqlul et al. (2015), SRI rice is the best alternative in places like Tanzania and many parts of Africa where there is suitable land for agricultural production but limited access to water. Simulations also indicated the sensitivity of SRI rice yields to drying and wetting periods.

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 Mkindo village in the Mvomero district. The scenarios that implemented continuous cropping of SRI rice, in combination with multiple cropping of fertilized maize with either irrigated, dry-season vegetables and fodder, or with irrigated, dry-season vegetables only, 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). The most preferred scenario in terms of income generation was the one that implemented multiple cropping of fertilized maize with irrigated vegetables only. In contrast, the scenario that included multiple cropping of rain-fed rice (rather than continuously cropped SRI rice) with irrigated vegetables and fodder did not differ greatly from the baseline, non-irrigated scenario.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies (especially in vitamin A) 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 relatively modest percentage of cropland in the area (just 24.86% of the total watershed area) also limits the expansion of SSI and cultivation of additional crops in the Mkindo watershed.

The results presented above raise a number of issues to be resolved in future modeling and field research. These include the need to identify: (1) the potential for use of shallow groundwater from SSI in areas too distant for use of surface water; (2) appropriate fertilizer amounts for more intensive cropping systems involving production of irrigated vegetable, fodder, and grain crops in the dry season; and (3) appropriate management of fertilizer and harvest practices for irrigated fodder production. 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

a) Crop management data for continuous cropping of rice and maize crops (baseline scenario).

Maize		Rice		
Practice	Dates	Practice	Dates	Amount
Tillage	10/10	Tillage	12/10	
Tillage	10/30	Tillage	12/15	
Planting	10/30	DAP fertilizer application	12/15	25 kg
Harvest	2/20	Transplanting	12/15	
		1st stage urea fertilizer application	1/7	50 kg
		2nd stage urea fertilizer application	3/2	50 kg
		Harvest	4/23	

Note: fertilizer is not applied for maize in the study watershed.

b) Crop management schedules for multiple cropping of rice-rice in the Mkindo watershed.

Rice rainy season	Date	Amounts/ remark	Rice dry season	Date	Amounts/ remark
Tillage	12/1		Tillage	5/1	
Tillage	12/15		Tillage	5/15	
1st stage urea fertilizer application	12/15	50 kg/ha	1st stage urea fertilizer application	5/15	50 kg/ha
Transplanting	12/15		Transplanting	5/15	
DAP fertilizer application	12/15	25 kg/ha	DAP fertilizer application	5/15	25 kg/ha
2nd stage urea fertilizer application	3/15	50 kg/ha	2nd stage urea fertilizer application	8/13	50 kg/ha
Harvest	4/26		Harvest	9/23	

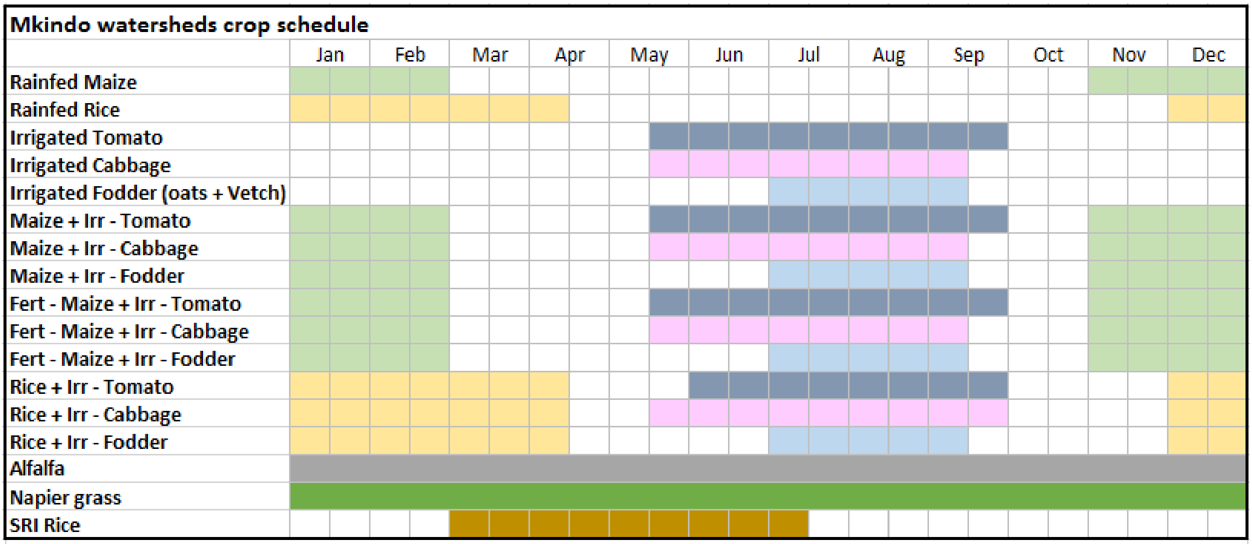
c) Crop management schedules for multiple cropping of maize-tomato in the Mkindo watershed.

Maize rainy season	Dates	Tomato dry season	Dates	Amount/remark
Tillage	10/10	Tillage	3/5	
Tillage	10/30	Tillage	3/20	
1st stage urea fertilizer application	NA	1st stage urea fertilizer application	3/20	34 kg/ha
DAP fertilizer application	NA	Transplanting	3/20	
Planting	10/30	Harvest	7/30	
2nd stage urea fertilizer application	NA			
Harvest	2/20			

Note: for the improved fertilizer rates scenario, an application of 50 kg/ha DAP and 25 kg/ha urea during planting and 25 kg/ha as side dress after 45 days from the planting date was applied.

Appendix A2

APEX crop management schedules and fertilization (type and application rate) for: a) maize; b) rice; c) tomato, cabbage and fodder (vetch + oats); d) SRI rice; e) alfalfa; and f) Napier grass



Where: Irr and Fert are irrigation and fetilizer applications, respectively.

a). Maize schedule with and without fertilizer

Maize Practice	Without fertilizer	With fertilizer
Tillage	10/10	10/10
Tillage	10/30	10/30
1st stage urea fertilizer application	Don't apply	10/30 (25 kg/ha)
DAP fertilizer application	Don't apply	10/30 (50 kg/ha)
Planting	10/30	10/30
2nd stage urea fertilizer application	Don't apply	12/20 (25kg/ha)
Harvest	2/20	2/20

b). Rice schedule

Rice Practice	Date	Notes
Tillage	11/15	
Tillage	11/30	
1st stage urea fertilizer application	11/30	50 kg/ha
Transplanting	11/30	
DAP fertilizer application	11/30	25 kg/ha
2nd stage urea fertilizer application	2/28	50 kg/ha
Harvest	4/9	

c). Tomato, Cabbage and Fodder schedule

Operations	Tomato	Cabbage	Fodder Practice (Oats/Vetch)
Tillage	4/30	4/30	6/16
Tillage	5/15	5/15	7/1
1st stage urea fertilizer application	5/15 (34 kg/ha)	5/15 (34 kg/ha)	7/1 (25 kg/ha)
Planting	5/15	5/15	7/1
DAP fertilizer application	don't apply	don't apply	7/1 (50 kg/ha)
2nd stage urea fertilizer application	don't apply	don't apply	8/10 (25 kg/ha)
Harvest	9/22	9/12	8/30

d). SRI Rice schedule

Operations	Date
Tillage	1/29/15
Tillage	2/18/15
Tillage	3/5/15
1st stage urea fertilizer application	3/5 (50 kg/ha)
Transplanting	3/5/15
DAP fertilizer application	3/5/15 (50 kg/ha)
2nd stage urea fertilizer application	6/3/15 (50 kg/ha)
Harvest	7/14/15

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

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