



***Ex Ante* Analysis of Small-Scale Irrigation Interventions in Kilosa**

Texas A&M University Integrated Decision Support System Team
USAID Feed the Future Innovation Laboratory for Small-Scale Irrigation

Jean-Claude Bizimana, Neville P. Clarke, Yihun T. Dile, Thomas J. Gerik, Jaehak Jeong,
Javier M. Osorio Leyton, James W. Richardson, Raghavan Srinivasan, and Abeyou W. Worqlul

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 Sokoine University of Agriculture; Cleophelia Roberts and Carlo Azzarri, both of IFPRI, for graciously providing the household survey used in our economic analyses; and Ben Lukuyu of ILRI for facilitating local contacts.

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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 Rudewa watershed, in the Kilosa district of the United Republic of Tanzania. The annual crops yields produced in the area are far below the 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 Kilosa, 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 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 Rudewa watershed. Cropland comprises a very small percentage (just 1.46%) of total land in the watershed; even when combined with irrigable pasture land, the area to be irrigated would comprise just 1.74% of total land in the watershed. Accordingly, the total annual volume of irrigation water withdrawn in the watershed would be less than 960,000 m³, or just 0.14% of the annual stream flow leaving the watershed. Moreover, simulations indicated that proposed SSI interventions would reduce average monthly stream flow by only 0.69%. Low flows were significantly affected by the withdrawal of irrigation water from rivers, but peak flows were not affected. This suggests that the proposed SSI interventions may not compromise the overall water balance significantly; however, the low flows may

be reduced and ecosystems that depend on the low flows may be affected. Some alternative surface water storage or groundwater extraction may be needed to supply human and livestock drinking water during periods of extreme low flows. Moreover, 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. The implementation of multiple cropping systems also affected simulated crop yields. Proper understanding and use of multiple cropping combinations could increase crop yields and improve soil health, but some combinations if under-fertilized would probably decrease productivity. For the fertilizer application scenarios simulated in this study, simulations indicated a significant increase in rice yield for each of the multiple cropping scenarios, with the highest rice yield resulting from multiple cropping of rice with fodder. Multiple cropping of maize with fodder significantly increased simulated maize yield, whereas multiple cropping of maize with cabbage decreased simulated maize yield slightly. Tomato and fodder yields decreased significantly when simulated as multiple crops with rain-fed rice and maize. Cabbage yields also decreased slightly in both multiple cropping scenarios. These reductions in simulated yields generally reflected increases in nitrogen stress to the affected crops, and suggest the need for further exploration of appropriate fertilization amounts for these particular multiple cropping combinations.

Simulations 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 Rudewa-Mbuyuni village in Kilosa 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 irrigated vegetables and fodder). Cash income increased as the irrigated area increased. The most preferred scenario in terms of income generation was the one that allocated the largest area of irrigable cropland to vegetables, fodder and SRI rice.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies (in vitamin A particularly) 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 such as stream flows in the dry season. The extremely modest percentages of cropland and irrigable pasture land in the area (together, just 1.74% of total land in the watershed) also limit the expansion of SSI and cultivation of additional crops in the Rudewa 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). Just as the adoption of science-based technology in the 1970s propelled Asia from famine to regional food surplus within 25 years (Djurfeldt et al. 2005; Hazell 2009), 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 Tanzania. 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 Rudewa watershed, located in the Kilosa 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 long rainy season and the dry season restricts rain-fed cropping to the rainy season. Annual crops yields produced in the Kilosa area 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 Kilosa'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 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 crops (rain-fed rice and maize) with several irrigated, dry-season crops. All three models also simulated fertilizing the maize crop at improved (higher) rates and cultivating certain perennial crops (e.g., Napier grass) on pastureland. To provide more detail at the field scale, APEX and FARMSIM also simulated 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 Rudewa watershed is located at 6°36' 29" S, 37°00'36.2" E, in the Kilosa district of Morogoro Region of Tanzania (fig. 1).

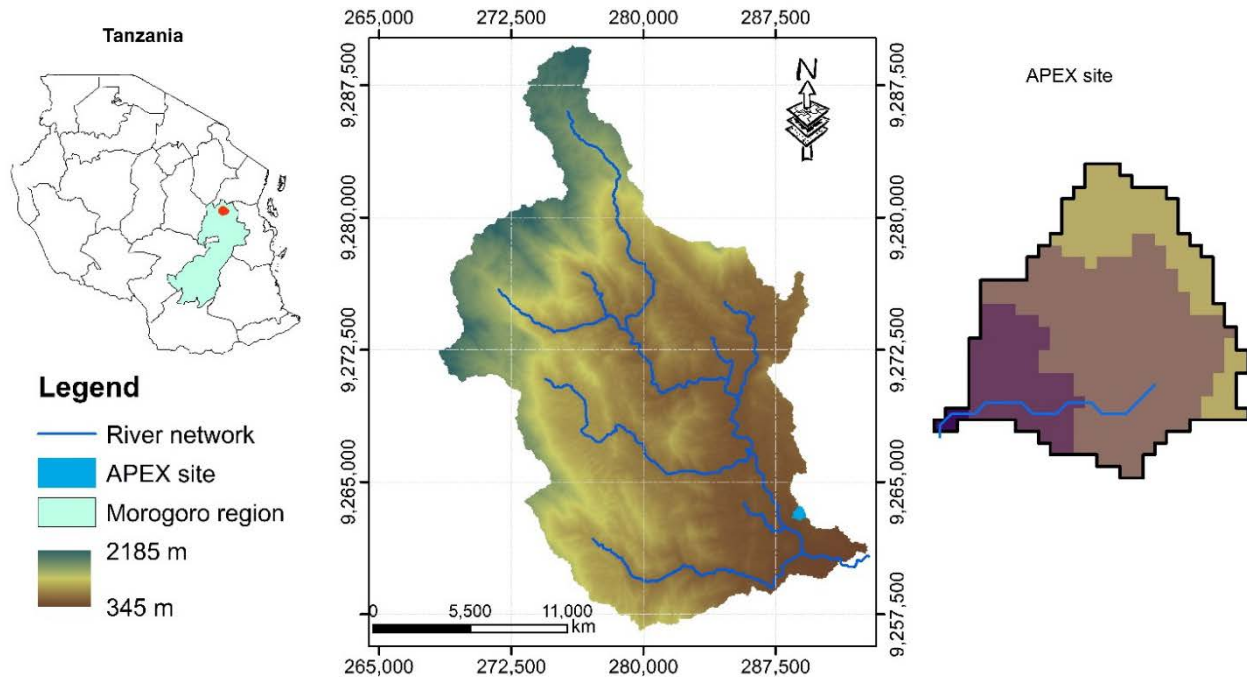


Figure 1. Rudewa watershed boundary, main streams and subarea 1114, simulated with APEX.

The watershed covers a 38,727.36-ha area, with elevation ranging from 433 to 2185 m amsl. Four types of land use were identified in the Rudewa watershed: forestland (76.32%), bush land (17.96%), pasture (4.27%), and cropland (1.46%) (SRTM 2015). Only one soil type, loam soil, was identified in the Rudewa watershed (FAO&ISRIC, 2013). The average percent slope of the watershed, computed from 30m-resolution Enhanced Shuttle Land Elevation Data, was approximately 26%. 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 maize and rice, cultivated in the rainy season. 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.

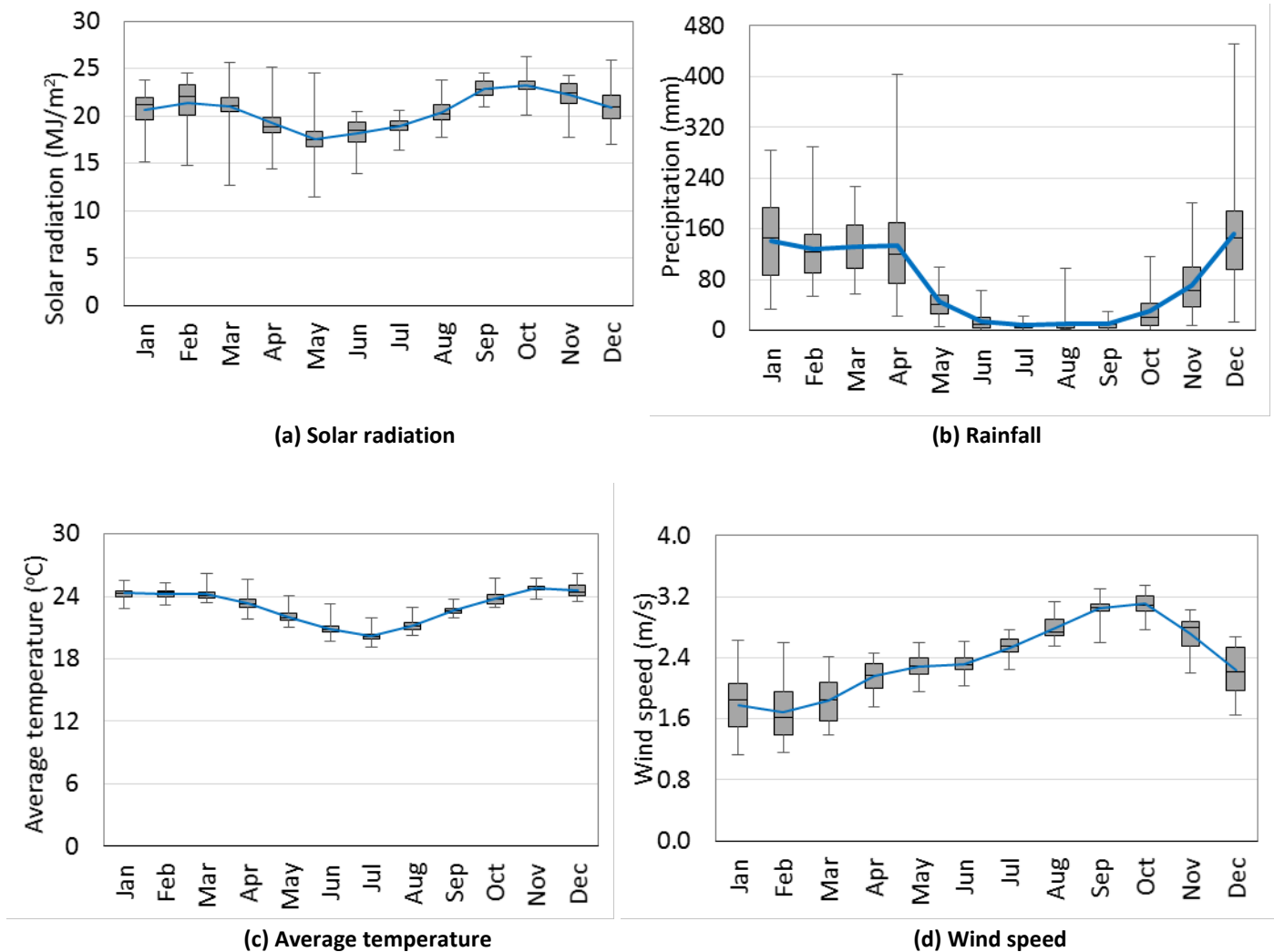


Figure 2. Monthly average weather data from a synoptic station from 1980 to 2010 (TMA 2015). The rectangle represents the first and third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum.

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 map, developed by combining more than 10 global datasets, 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#anchor>). 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 Kilosa 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	Kilosa	1.50	1.50
FAO (1981 to 2010)	Tanzania	--	1.50	1.73

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 Rudewa watershed. The 38,727.36-ha watershed was subdivided into 1381 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 km². 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.

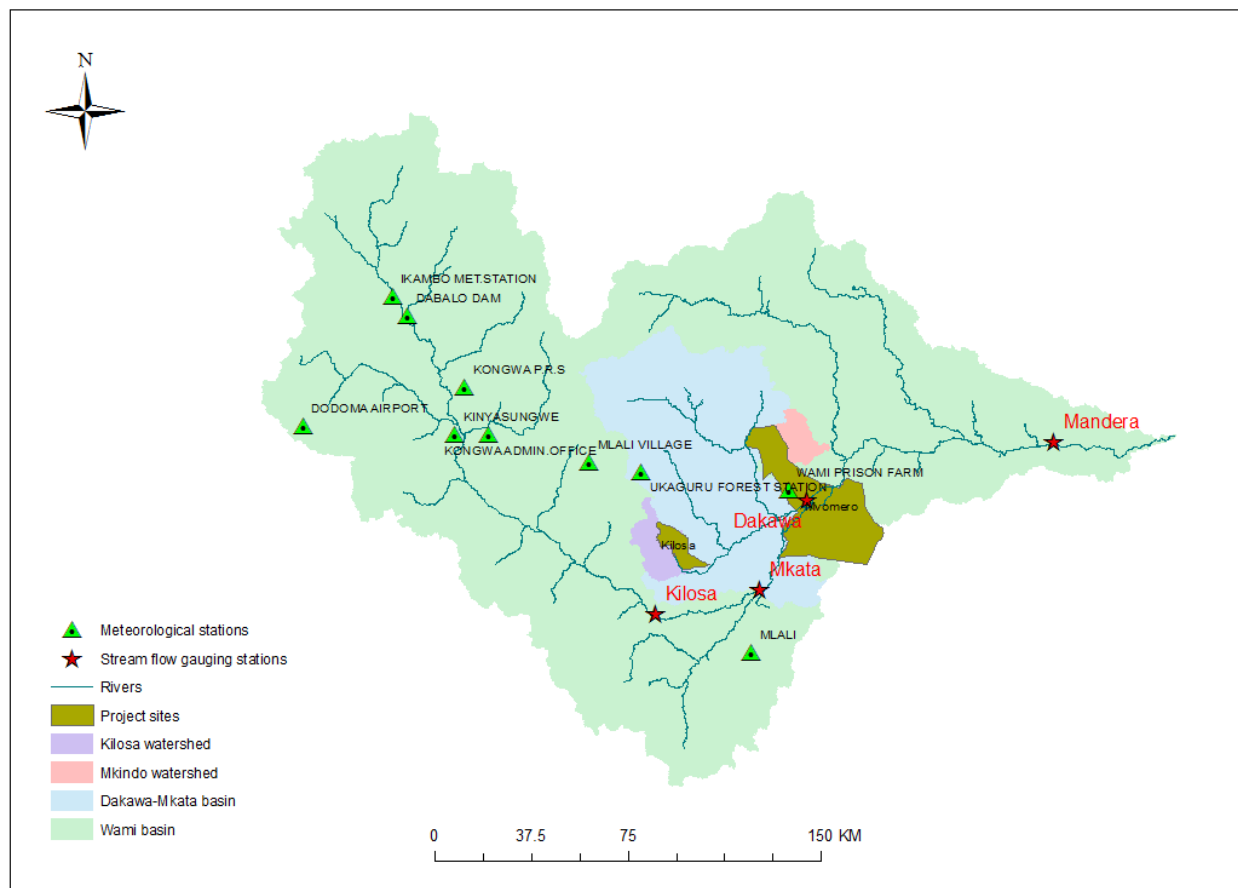


Figure 3. Location of the Rudewa watershed in the Wami basin.

For APEX, a sub-watershed dominated by agricultural land (subarea 1114, equivalent to SWAT's subbasin 1114) 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 1114 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 Rudewa watershed (fig. 1), and is approximately 37 ha in area, with elevation varying from 458 to 541 mamsl. The average percent slope of the sub-watershed is approximately 5% (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 SPAM 2005 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; fertilizing the maize crop at improved (higher) rates; and cultivating certain perennial crops (e.g., Napier grass) on pastureland.

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 1.46% 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.

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 the grain crops (maize and rain-fed rice) in the rainy season with irrigated tomato, cabbage, and fodder (oats/vetch) in the dry season, as well as the continuous cropping of SRI rice as an alternative to traditional, rain-fed rice.

The SRI method for rice cultivation was introduced in Tanzania in 2009 to strengthen the country's food security, and is practiced in the Morogoro region. Contrary to the traditional approach of growing rice in rain-fed, 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 Rudewa Mbuyuni, a village located in the Kilosa district, for five years to provide an economic perspective on promising SSI interventions identified by SWAT and APEX simulations. The majority of the population in Rudewa Mbuyuni derive their livelihoods from crop and livestock production. A 2015 IFPRI survey indicated that the major crops grown, by area, in Rudewa Mbuyuni are maize (488 ha) and paddy rice (408 ha), on an estimated total cropland of 1411 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 Rudewa Mbuyuni is limited, occupying only about 177 ha. The main types of livestock produced are cattle, goats, pigs and chickens.

In addition to the baseline scenario, FARMSIM simulated three alternative scenarios, each implementing SSI, using diverted river water, on irrigable land in Rudewa Mbuyuni. 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. The second and third alternative scenarios differ only in the cropping area dedicated to vegetables, SRI rice and fodder. Irrigable cropland dedicated to these crops increased incrementally from the first to the second to the third alternative scenario. (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 was 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.

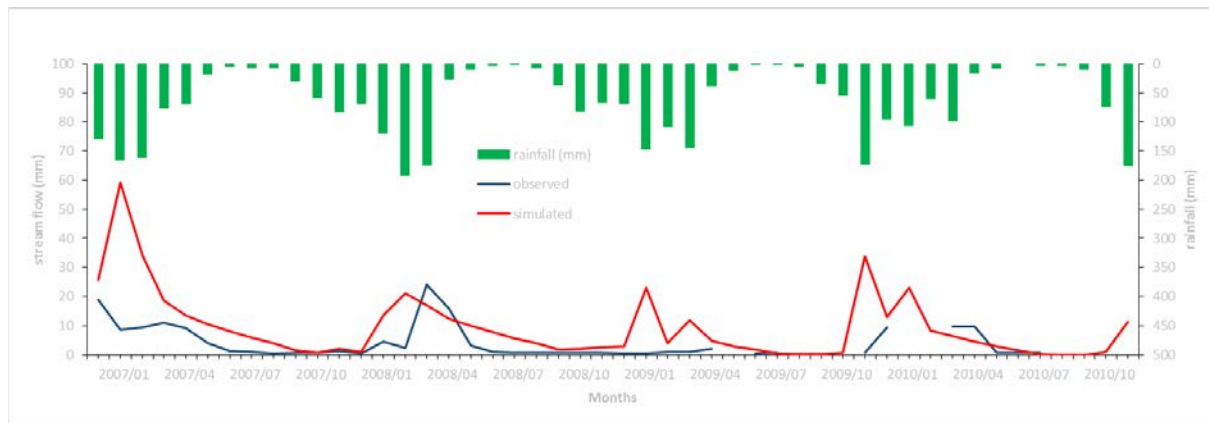


Fig. 4. Monthly observed rainfall vs observed and simulated stream flow at the outlet of the calibrated watershed. Note: the axis for the rainfall is reversed.

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 Rudewa watershed.

Table 2. Calibrated SWAT parameters for the Rudewa 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-Sutcliffe Efficiency (NSE) value of 0.83 and R-square value of 0.86. 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).

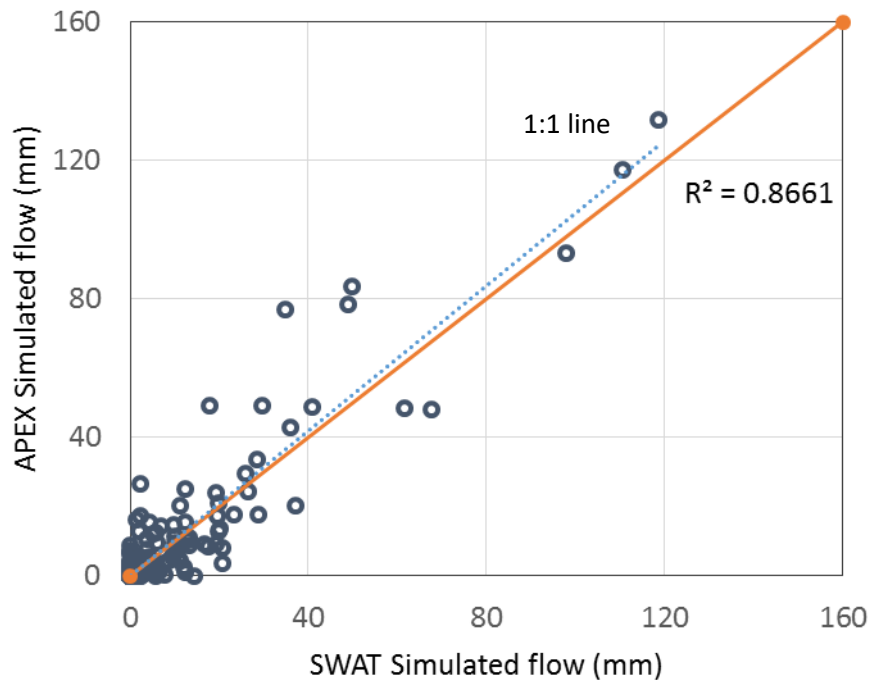


Figure 5: Scatter plot of SWAT and APEX simulated flow for Rudewa watershed

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

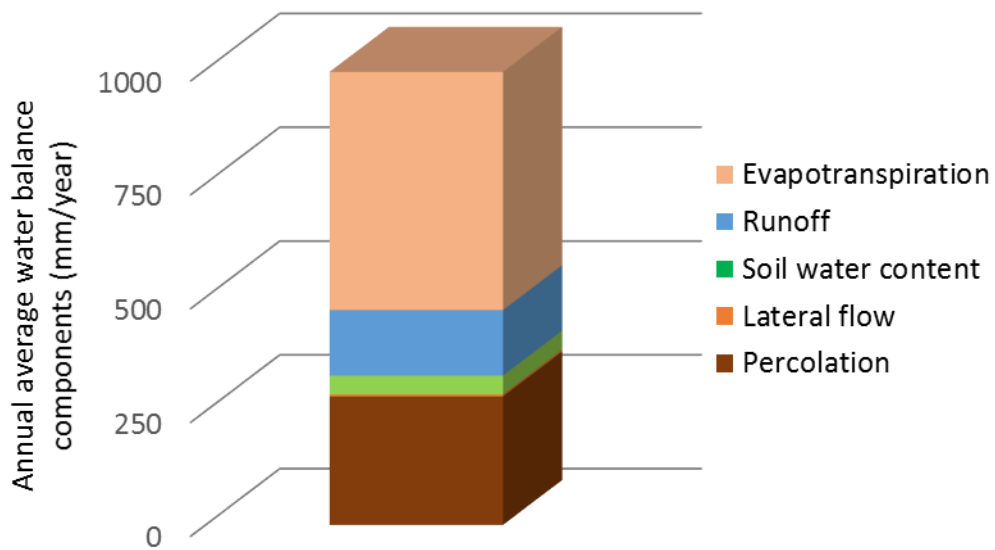


Figure 6. Water balance components of the calibrated APEX model for Rudewa watershed

4.1.3 Base period crop yield simulation. APEX captured the observed yields of maize and rice for the year 2005 well, with 7.4% and 5.6% 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 10%; RMSE are 0.63 t/ha and 0.54 t/ha for maize and rice yields, respectively. The FAO yield estimate has a higher variance than the APEX result, as it is estimated for the whole of Tanzania.

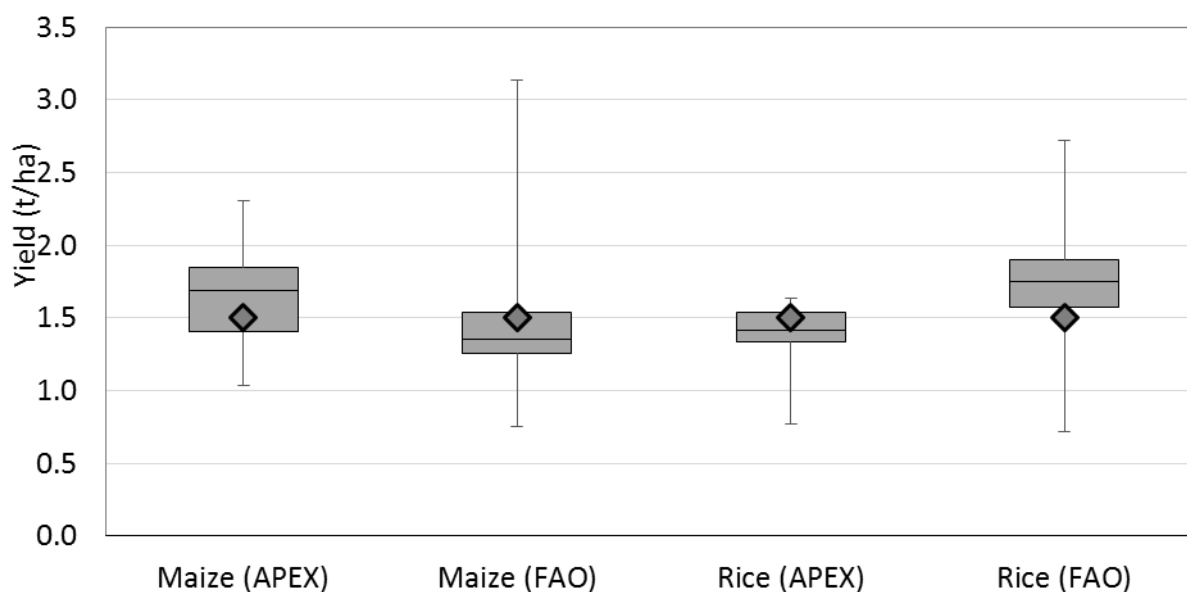


Figure 7: Comparison of APEX vs. FAOSTAT maize and rice yields from 1981 to 2010. The diamonds represent the SPAM crop yields for 2005.

4.2 Hydrology. For Tanzanian sites, expert opinion and field research 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% (366.75 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 whenever insufficient soil moisture stressed crop growth by 25%);
- ii. on agricultural land with slopes greater than 8% (198.83 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 to the tomato crop was equal to 25%)
- iii. on agricultural land with slopes greater than 8% (198.83 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 to the tomato crop was equal to 25%); and
- iv. on pasture land (106.47 ha): cultivation of a perennial fodder crop (Napier grass), with irrigation applied whenever water stress reduced crop growth by 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 annual groundwater and surface water resources in the Rudewa watershed are presented in figure 8. The simulated average annual groundwater recharge varied from 34 mm to 147 mm, and annual surface runoff ranged from 42 mm to 113 mm (fig. 8). Higher groundwater recharge and surface runoff generation were observed at the downstream portion of the watershed, which is an agricultural area. Moreover, high surface runoff was also observed on pasture land. For the Rudewa watershed, with a catchment area of 38,727.36 ha, the average annual volumetric groundwater recharge and surface runoff were over 30 million m³ and 22 million m³, respectively.

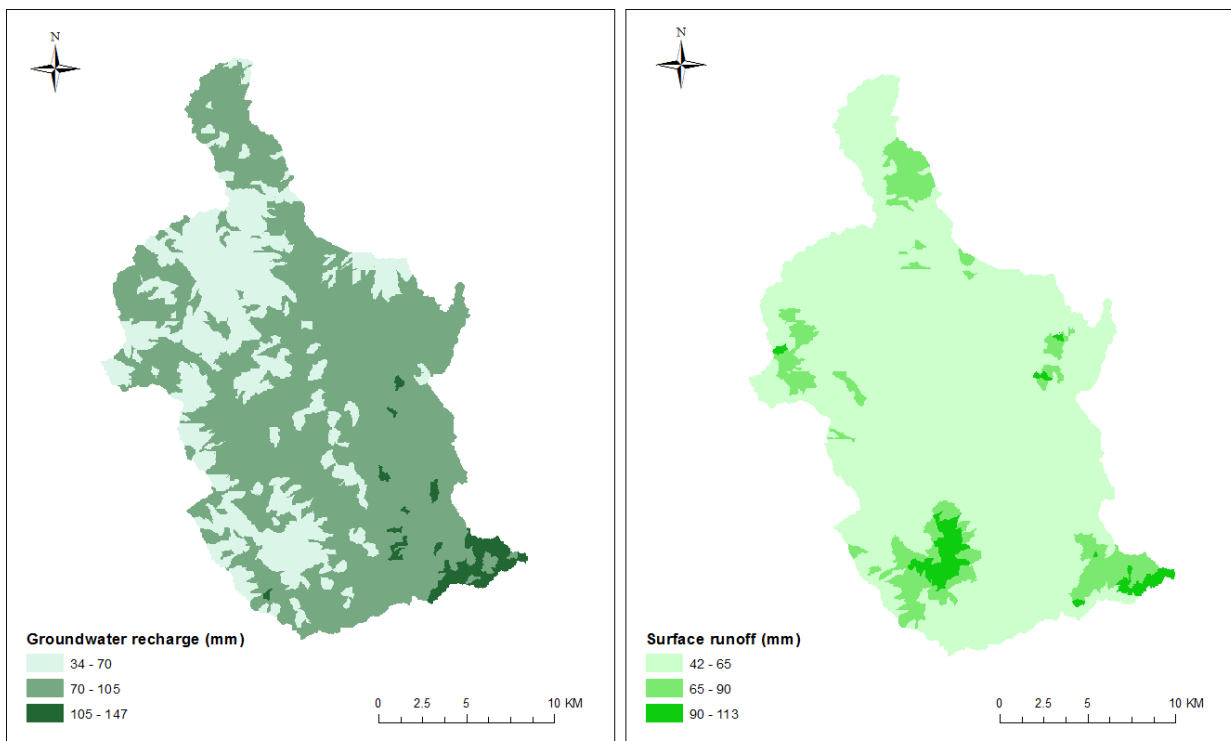


Figure 8. Water resources potential in the Rudewa watershed: a) average annual groundwater recharge; and b) surface runoff.

4.2.2 Watershed water balance impacts of the SSI (ex-ante) scenario. The average annual rainfall in the Rudewa watershed for the period from 1980 to 2010 was 678 mm. Streamflow was about 16% of annual rainfall, and 79% 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 59% of stream flow in the watershed, and surface runoff contributed 41%.

Implementation of irrigated, dry-season rice, tomato and fodder production using irrigation from rivers did not affect overall water balance dynamics in the watershed, because the irrigated area comprised just 1.74% (672.05 ha) of the entire watershed, including irrigation in the pasture land.

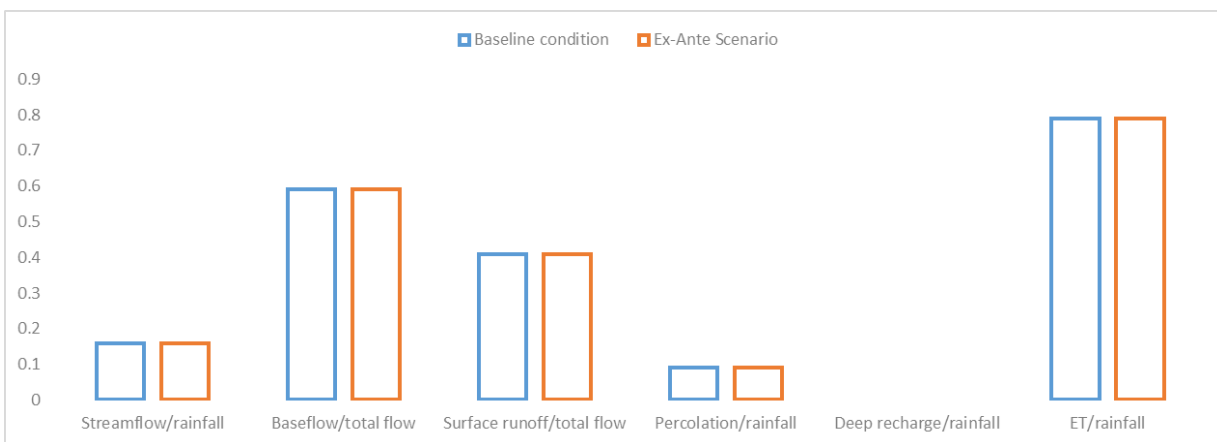


Figure 9. Water balance partitioning for the Rudewa watershed in the baseline scenario and irrigated rice/tomato (SSI, ex ante) scenario.

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 1.0 mm to 483 mm, depending on the 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 $56 m^3$ to $125,150 m^3$. The total annual volume of irrigation water withdrawn was $958,878 m^3$, or approximately 0.14% 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).

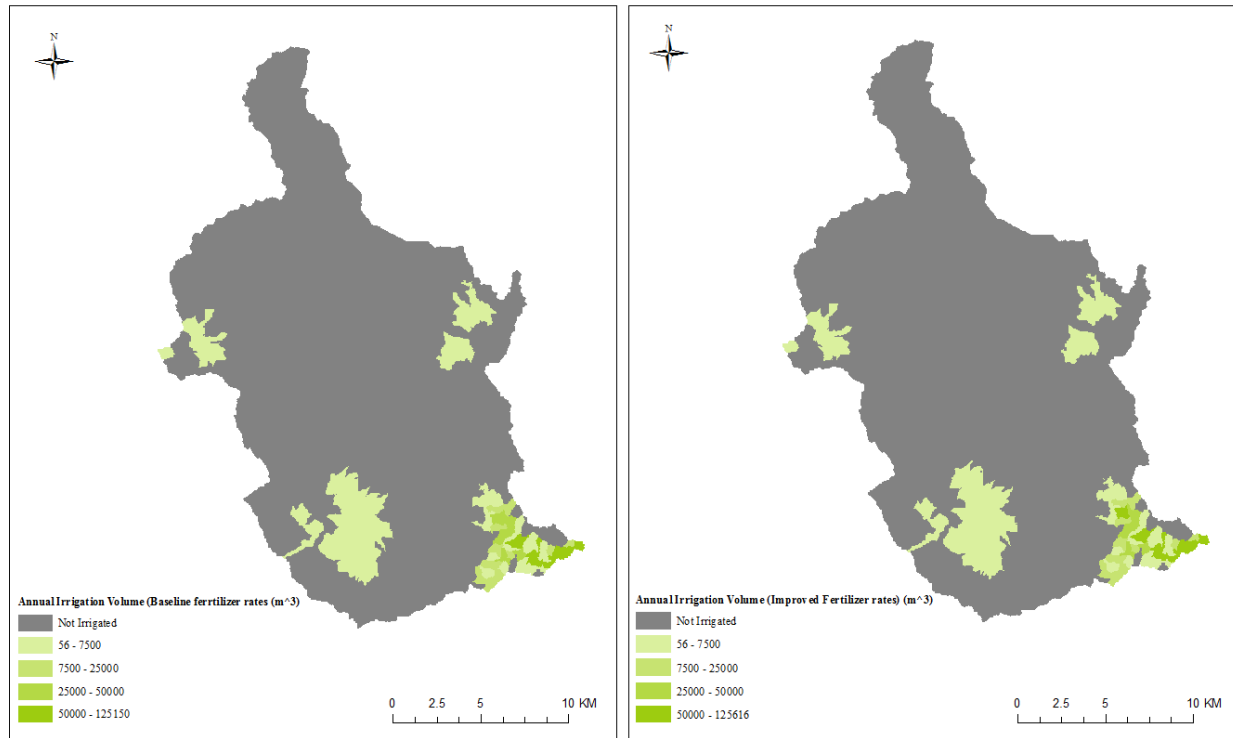


Figure 10. Average annual irrigation volumes (in m³) for dry-season, irrigated rice, tomato, and forage production where: a) rainy season crops are fertilized at baseline fertilizer rates, and b) the rainy-season maize crop is fertilized at improved fertilizer rates.

4.2.4 Changes in stream flows. Implementation of the proposed SSI interventions resulted in a very slight reduction in the average stream flow at the outlet of the Rudewa watershed. In the baseline scenario, the average monthly stream flow from 1980 to 2010 was 1.68 m³/sec; the proposed SSI interventions reduced the average monthly stream flow by only 0.69%, to 1.66 m³/sec. The average monthly stream flows varied only slightly when the rainy-season maize crop was fertilized at improved, rather than baseline, rates. The reductions in monthly stream flow were so small that they were not reflected in the stream flow hydrograph plot (fig. 11). These results suggest that implementation of the proposed SSI interventions would not compromise the total downstream flows; however, the low flows may decrease significantly.

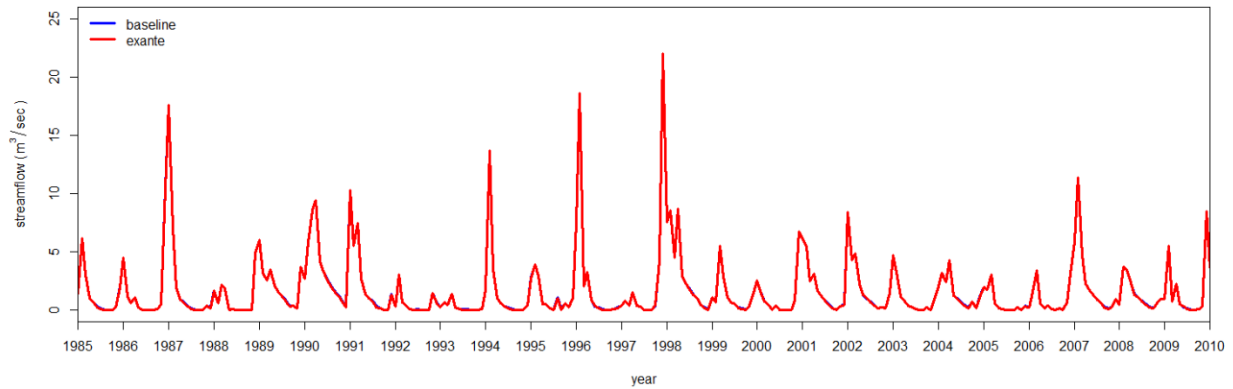


Figure 11. Stream flow at the outlet of the Rudewa watershed for the baseline scenario and SSI (ex ante) rice/tomato scenario. The reductions in stream flow was so small that the stream flow hydrographs with and without irrigation look identical.

The flow duration curve indicates that there was not noticeable change in the high flows with the implementation of irrigation for dry-season crops by diverting water from streams (fig. 12). For example, at the 10% probability of exceedance, the reduction in stream flows was 0.02% and the monthly stream flow at 50% probability of exceedance was reduced by only 0.74%. However, there was a significant reduction with stream flows at the low flows. For example, at 80% probability of exceedance, the reduction in stream flows was 9.8%; however, the reduction in stream flows was 87.5% at the 90% probability of exceedance.

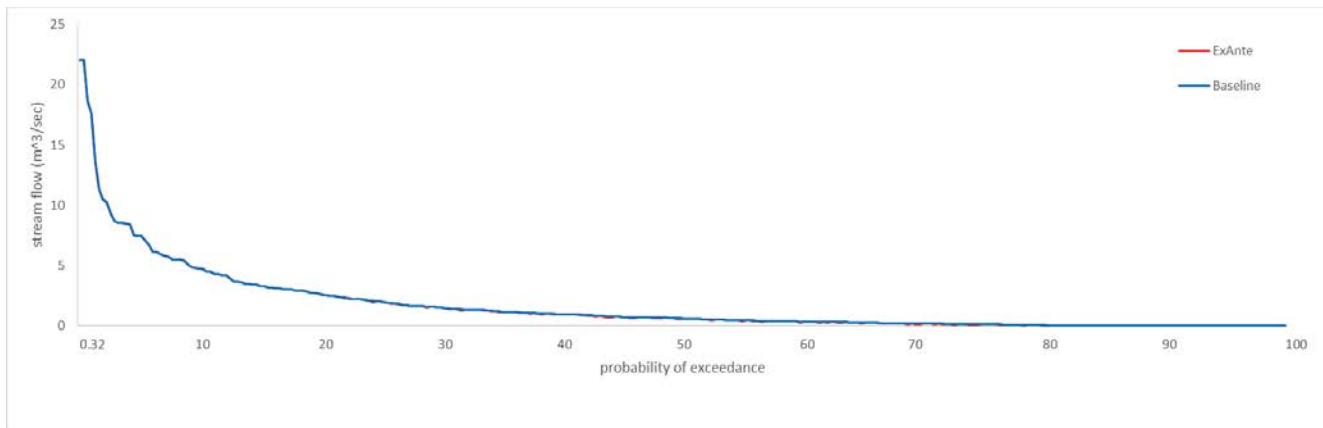


Figure 12. Flow duration curve for the monthly stream flow in the baseline scenario and irrigated rice/tomato scenario.

Simulations indicated that there is ample water available for SSI in the Rudewa watershed. Agricultural land comprises a very small percentage (just 1.46%) of total land in the watershed; even when combined with irrigable pasture land, the area to be irrigated would comprise just 1.74% of total land in the watershed. Accordingly, the total annual volume of irrigation water withdrawn in the watershed was

less than 960,000 m³, or just 0.14% of the annual stream flow leaving the watershed. Moreover, simulations indicated that proposed SSI interventions would reduce average monthly stream flow by only 0.69%. Peak flows were not affected by the withdrawal of irrigation water from rivers; however, extreme low flows were significantly affected. This suggests that alternative sources of drinking water for humans and livestock will be needed during periods of extreme low flows in the depths of the dry season. These sources might include surface storage of water captured during the wet season or withdrawals from shallow aquifers.

Although simulations indicated that there is ample water available for irrigation in the Rudewa watershed, there is little currently uncultivated agricultural land (with slopes less than 8%) available for cultivation close to rivers in the watershed. Suitable cultivated fields that were close to rivers received sufficient amounts of water for irrigation, but those suitable fields which were far from rivers received less irrigation. Significant expansion of proposed SSI interventions will therefore also 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 (rice and maize) in the rainy season with irrigated crops in the dry season (i.e. cabbage, tomato, and oats/vetch).

Alternative scenario 2: multiple cropping of rain-fed, fertilized maize (using 50 kg/ha of urea in split applications and 50 kg/ha of DAP) in the rainy season, with irrigated crops in the dry season (i.e. cabbage, tomato, and fodder).

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

Alternate scenario 4: continuous cropping of 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 simulated crops (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, with a p-value of less than 0.05. Multiple cropping of maize with fodder (as opposed to continuous cropping of maize) increased maize yield by 50%, whereas multiple cropping of maize with cabbage increased the nitrogen stress days by 8.5 % and consequently decreased maize yield by 14%. The simulation indicated that fodder (vetch + oats) enriched soil nitrogen and consequently increased the subsequent maize yield. The simulation did not show any significant difference between yields of continuously cropped maize and maize grown as a multiple crop with tomato.

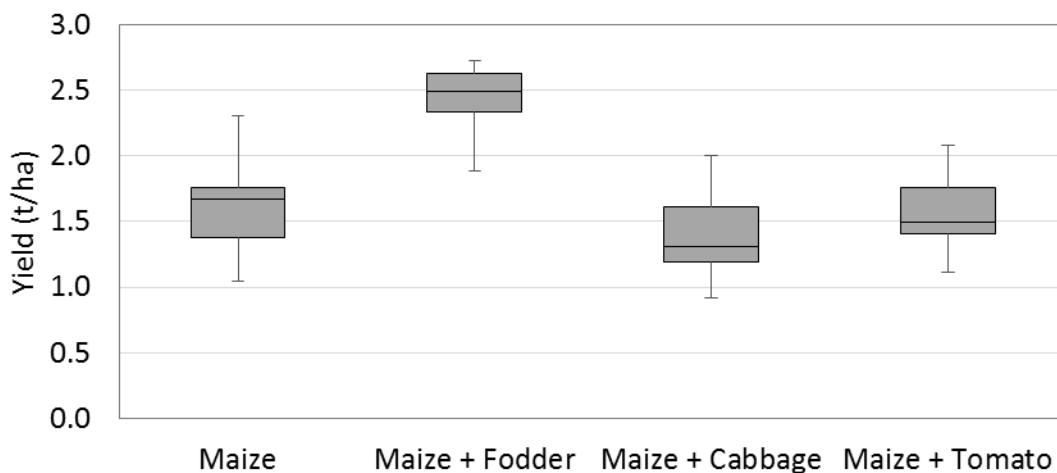


Figure 13. Maize yields when continuously cropped and when grown as a multiple crop with fodder, cabbage and tomato (from 1981 to 2010). The rectangle box represents the first and third quartile, median is represented by a segment inside the rectangle and whiskers above and below represent minimum and 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 indicated a significant increase in rice yield for each of the three multiple cropping scenarios, and the variability of the rice yield decreased significantly. Highest rice yield was observed with the multiple cropping of rice and fodder (a 32% increase over the continuously cropped rice yield); rice yield increased approximately 19% (as compared to the continuously cropped rice yield) with multiple cropping of rice with tomato and with cabbage. These increases in rice yields were due to increased residual nitrogen and soil moisture from the preceding crops.

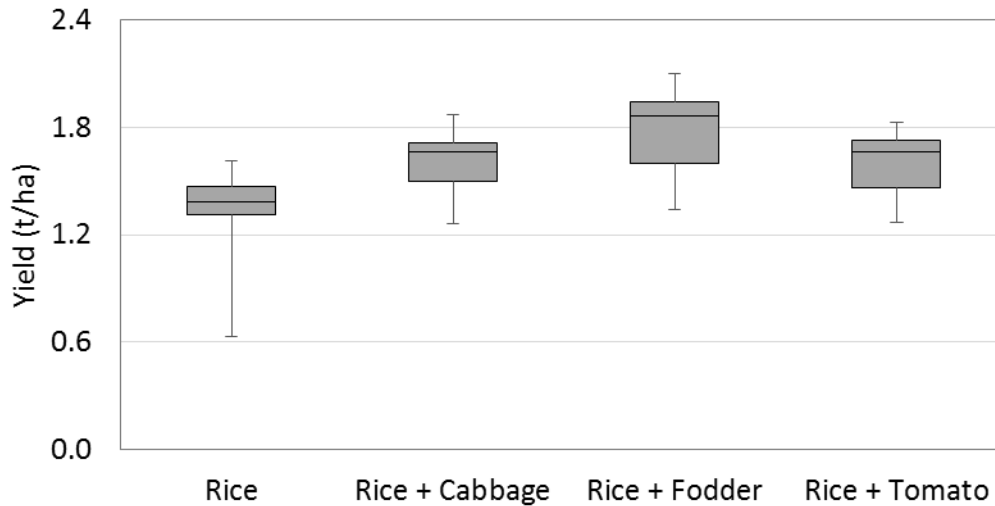


Figure 14. Yields of rain-fed rice when continuously cropped and when grown as a multiple crop with fodder, cabbage and tomato (1981 to 2010)

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. When grown as a multiple crop with maize and rice, tomato yields decreased by 53% and 25%, respectively (fig. 15). The nitrogen stress level increased with the multiple cropping of tomato with rice and maize, indicating that the rice and maize crops took the mineralized soil nitrogen, reducing the residual nitrogen for tomato. Cabbage yield decreased by 10% and 5%, respectively, when grown as a multiple crop with maize and rice (fig. 16). Fodder yield declined by 21% when grown as a multiple crop with maize, and by 15% when grown as a multiple crop with rain-fed rice (fig. 17).

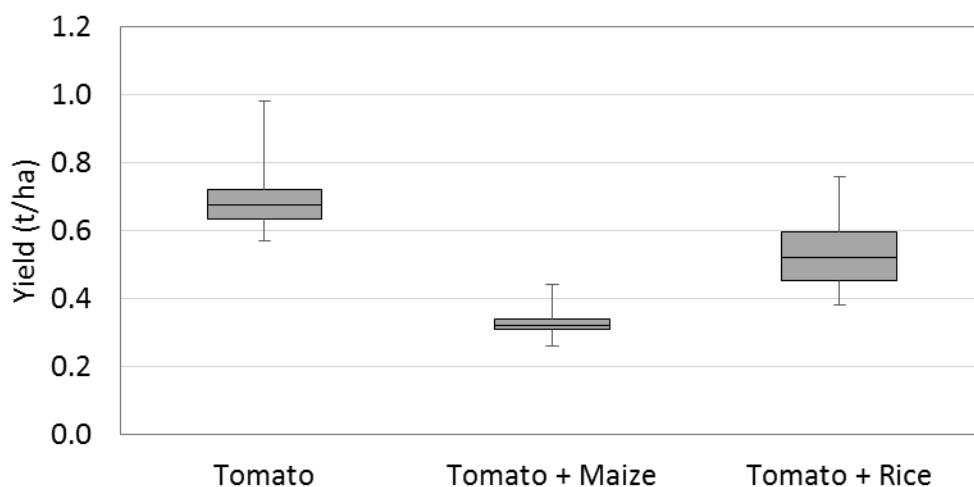


Figure 15. Tomato yield when continuously cropped, and when grown as a multiple crop with maize (with and without fertilizer) and with rain-fed rice (1981 to 2010)

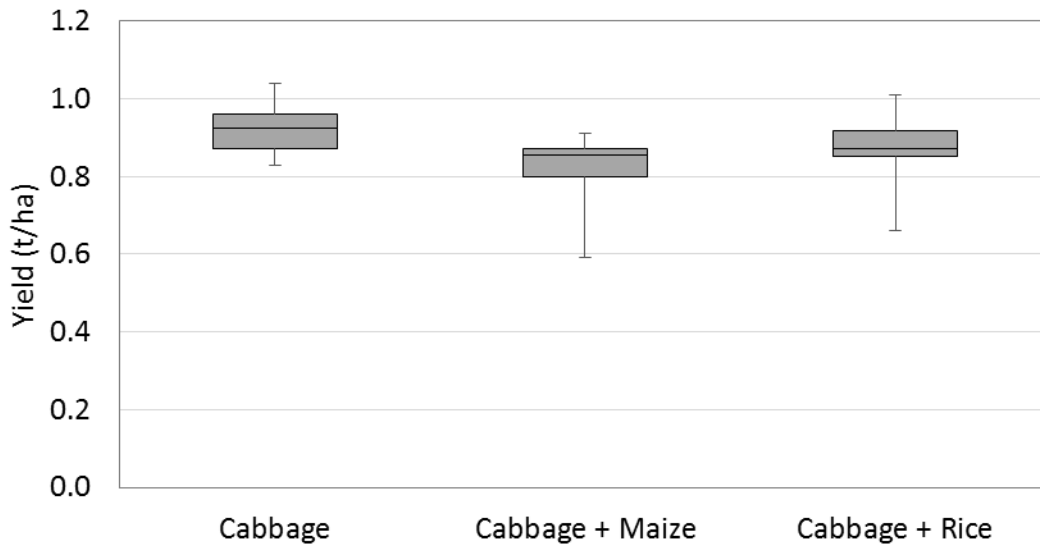


Figure 16. Cabbage yield when continuously cropped, and when grown as a multiple crop with maize (with and without fertilizer) and with rain-fed rice (1981 to 2010)

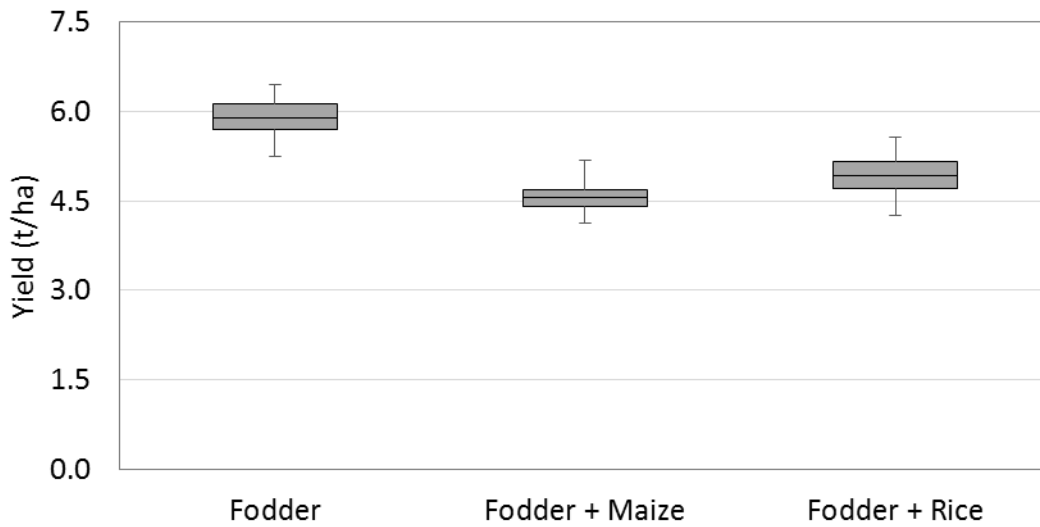


Figure 17. Fodder yield when continuously cropped, and when grown as a multiple crop with maize and rain-fed rice (1981 to 2010)

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 increased the yield of continuously cropped maize by approximately 83% 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. As compared to the continuously cropped, fertilized maize yield, fertilized maize yield increased by 29% when planted after fodder, but was not significantly affected

when planted after cabbage and tomato (fig. 18), suggesting that fodder legumes would supplement nitrogen fertilizer in this cropping system.

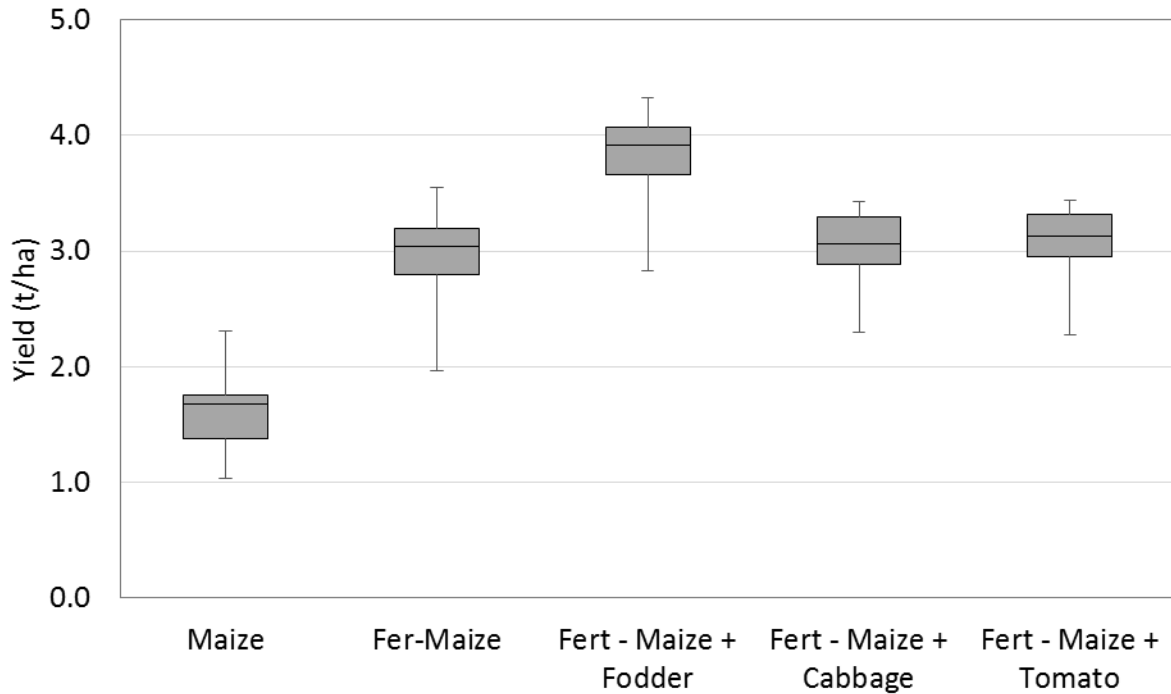


Figure 18. Continuously cropped, unfertilized maize yield, compared with yields of continuously cropped, fertilized maize, and fertilized maize grown in a multiple cropping system (1981 to 2010).

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 the soil 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 130, 23 and 3 days per year for nitrogen, water, and temperature, respectively. Alfalfa was stressed for water and temperature for an average of 78 and 3 days per year, respectively. Due to the absence of observed yield data in the Kilosa area, we were unable to calibrate the yields, but comparison with the study by Zhang et al. (2011) indicates that the simulation results are reasonable.

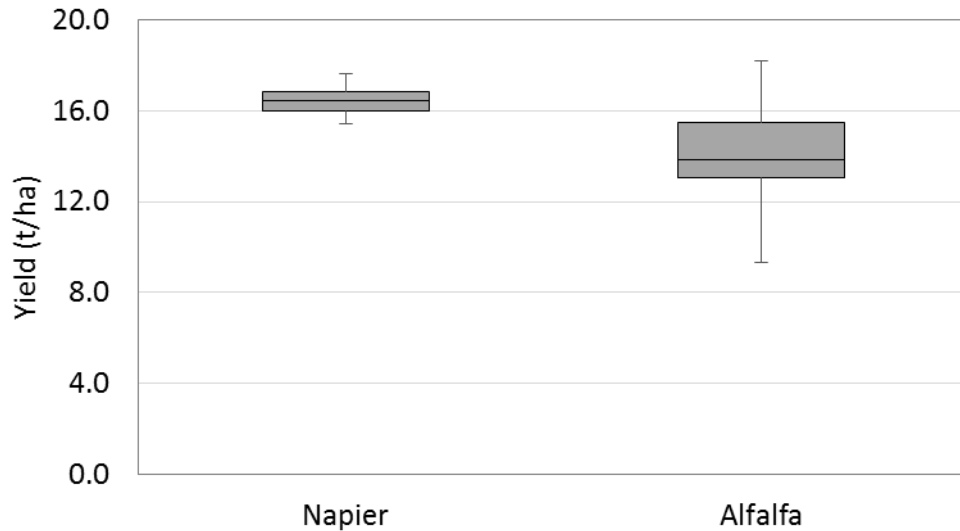


Figure 19. Yields of Napier grass and Alfalfa as perennial crops (1981 to 2010)

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 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 45% reduction in crop yield (fig. 20).

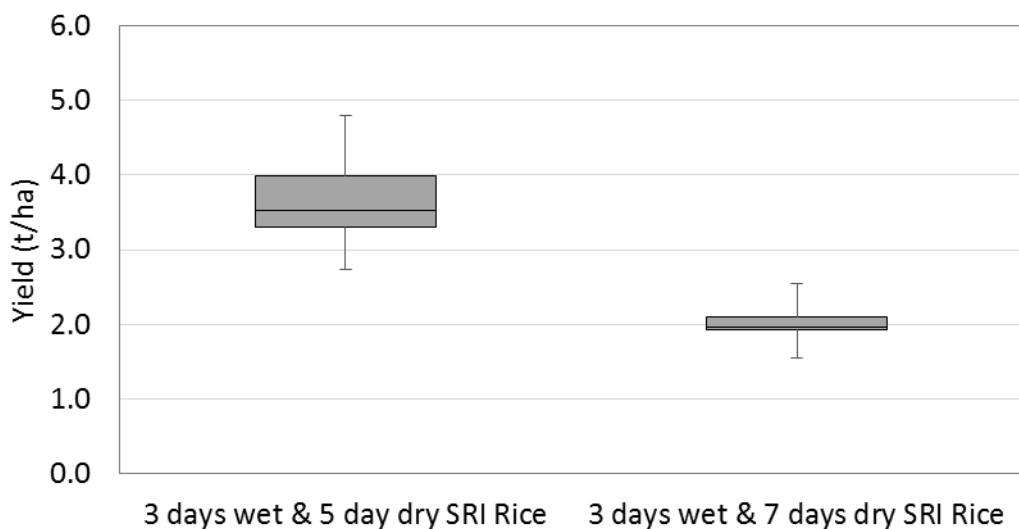


Figure 20. SRI rice yield simulation for 3 days wetting and 5 and 7 days drying (1981 to 2010)

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. Irrigation for dry season crops was applied to fill the root zone soil moisture to field capacity; accordingly, the irrigated crops did not produce runoff and the sediment loss was very low. Multiple cropping of maize with tomato, cabbage, and fodder did not produce significant changes in runoff (at a p-value of less than 0.05) for either scenario.

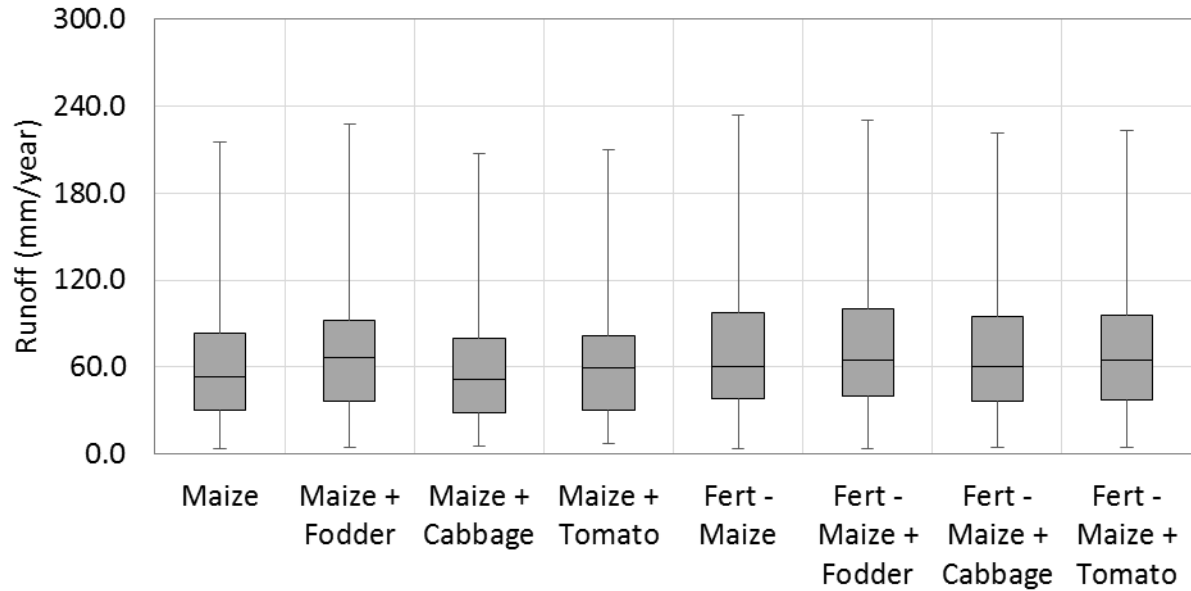


Figure 21. Runoff for alternative scenarios 1 and 2

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 38 t/ha. Multiple cropping of rain-fed maize with fodder, cabbage and tomato in did not significantly change sediment yields compared with the baseline scenario.

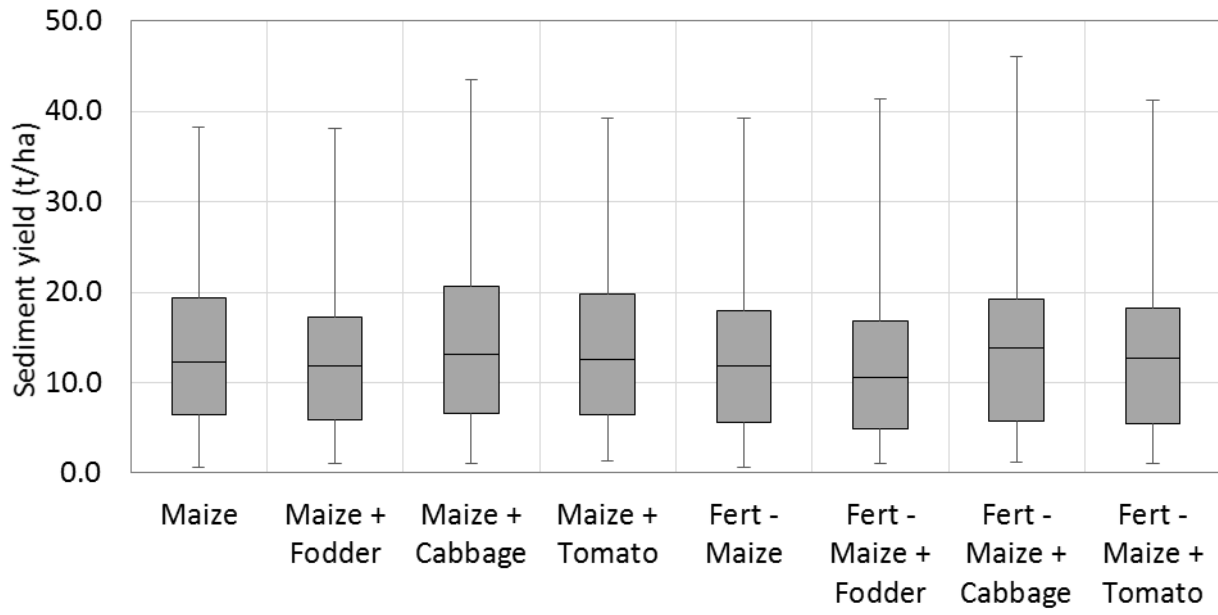


Figure 22. Sediment yields for alternative scenarios 1 and 2

Alternative scenarios 3 and 4. APEX simulations indicated that continuous cropping of alfalfa and Napier grass would reduce soil erosion by 86% and 98%, respectively, compared with the baseline scenario; however, alfalfa and Napier grass did not reduce simulated runoff yields (fig. 23). Since dikes were constructed on the perimeter of the rice fields and the amount of water applied in the wetting period (15 mm) was close to evapotranspiration requirements, continuous cropping of SRI Rice simulated for 5 and 7 drying days reduced both soil and runoff losses significantly compared to baseline.

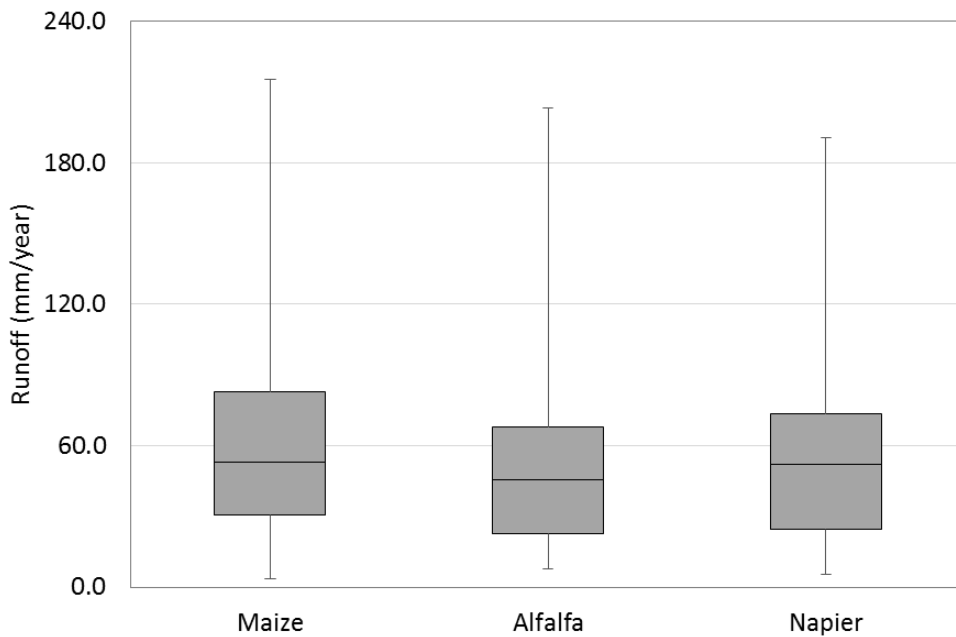


Figure 23. Runoff yields of alternative scenario 3 compared with baseline scenario

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 (tomato, cabbage and vetch/oats) are grown during the dry season.

Alts. 2 and 3 (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 (tomato, cabbage and vetch/oats) 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.

The cropping area for maize remained constant in each of the three alternative scenarios; however, the cropping areas for vegetables, fodder and rice were progressively increased in each of the alternative scenarios (from Alt. 1 to Alt. 3). Accordingly, the second and third alternative scenarios differed only in the total area allocated to vegetables, fodder, and rice (with Alt. 3 allocating the largest area to these crops of any of the four scenarios).

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, for example, 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 in combination with increased fertilization of maize and irrigation of the dry-season crops (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. The scenario allocating maximum cropping areas to vegetables, fodder and rice (Alt. 3) is preferable to the other scenarios for all 500 draws of the Monte Carlo farm model. Cultivation of rain-fed rice in combination with increased fertilization of maize and irrigation of vegetables (Alt. 1) perform better than the baseline scenario.

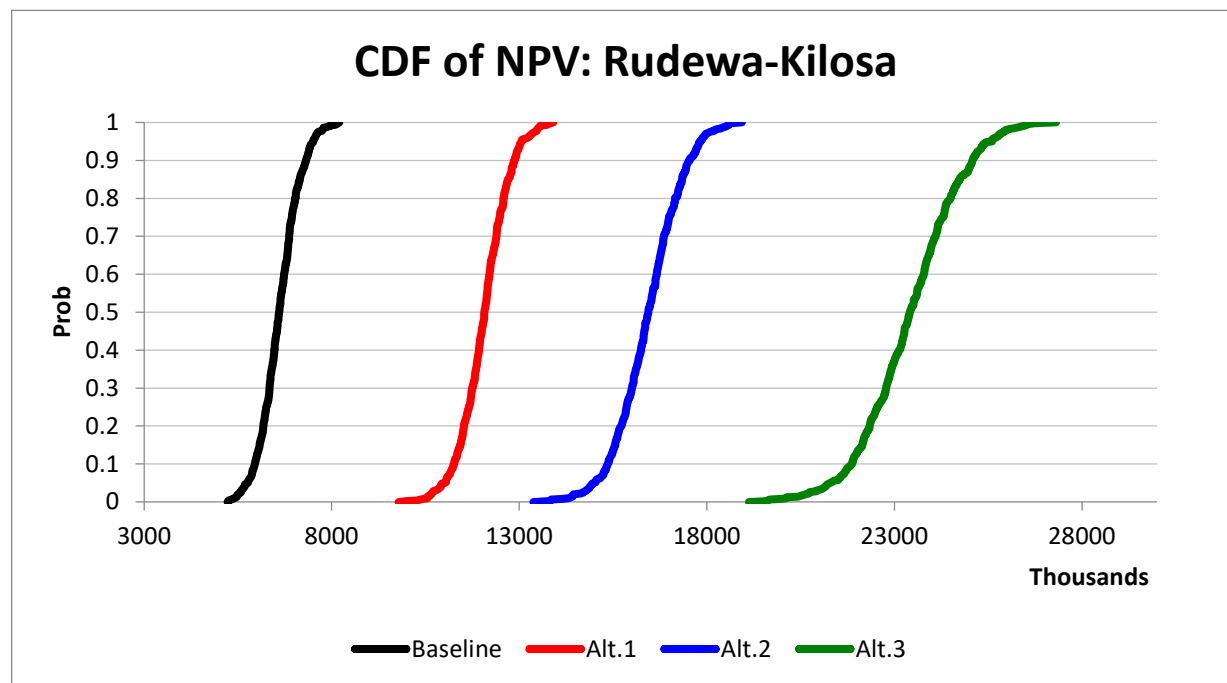


Figure 24a. Cumulative distribution function of NPV for Rudewa Mbuyuni village

The stoplight chart below shows the probabilities in each of the four scenarios of NPV being less than 6,600,000 TSh (Tanzanian Shillings) (red), greater than 16,600,000 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 second-best performing alternative scenario (Alt. 2) for the upper bound. In the baseline scenario, there is a 50% chance that NPV will be less than 6,600,000 TSh, and a 0% chance that NPV will exceed 16,600,000 TSh. In contrast, a farmer who adopts the SRI system and applies irrigation and increased fertilization rates for maize (Alts. 2 and 3) has a 43% and 100% chance, respectively, of generating NPV greater than 16,600,000 TSh; in both these scenarios, there is a 0% chance that NPV will be less than 6,600,000 TSh. Note that, as in the CDF graph, the scenario allocating maximum potential irrigable land to vegetables, SRI rice, and fodder (Alt. 3) generates the highest NPV.

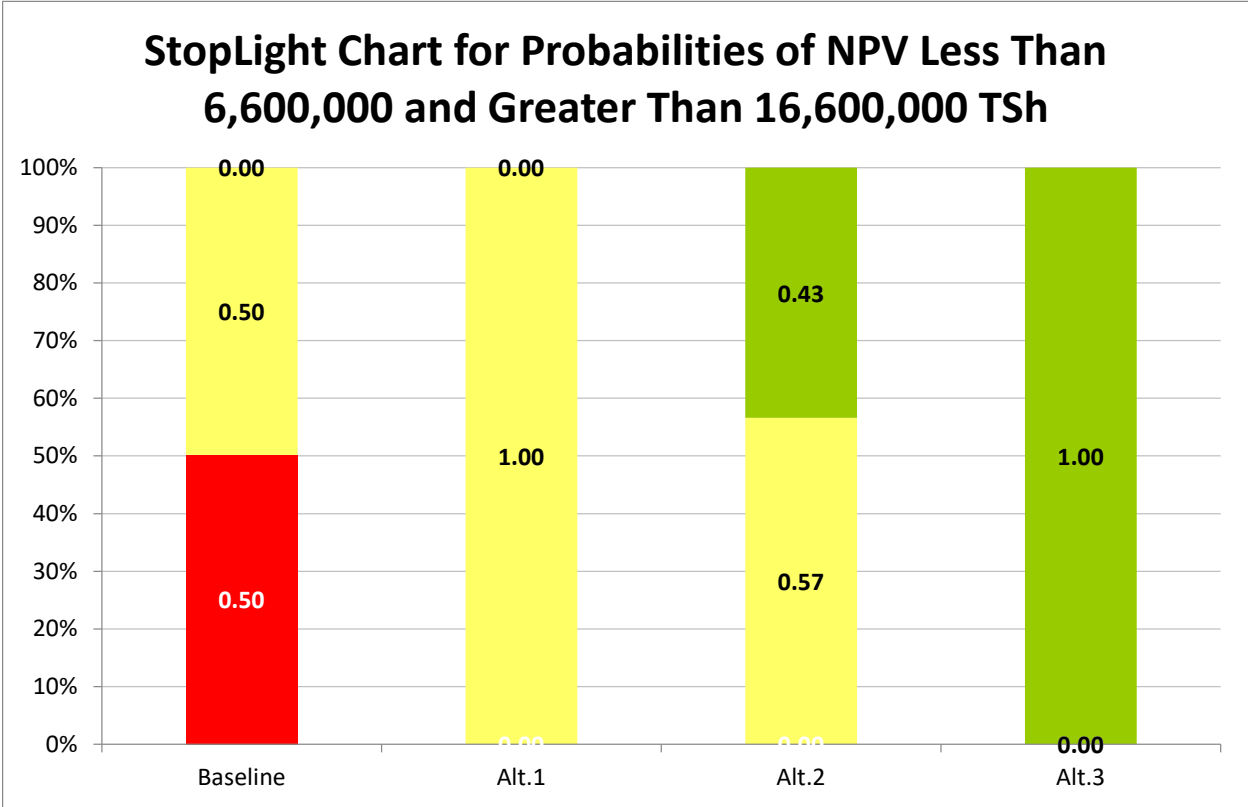


Figure 24b. StopLight chart of NPV for Rudewa Mbuyuni village

4.4.2 NCFI. The CDF graph in figure 25a shows a significant difference between the baseline and alternative scenarios in terms of the annual NCFI. The alternative scenarios adopting the SRI system for rice production (Alts. 2 and 3) generated higher NCFI than the other two scenarios; moreover, the scenario that allocated maximum cropping area to vegetables, fodder and rice (Alt. 3) performed better than all other scenarios (Baseline and Alts.1 and 2) for all 500 draws of the model, as its CDF values lie completely to the right of the other scenarios. The scenario combining rain-fed rice production with irrigation and increased fertilizer rates for maize (Alt. 1) performs better than the baseline scenario.

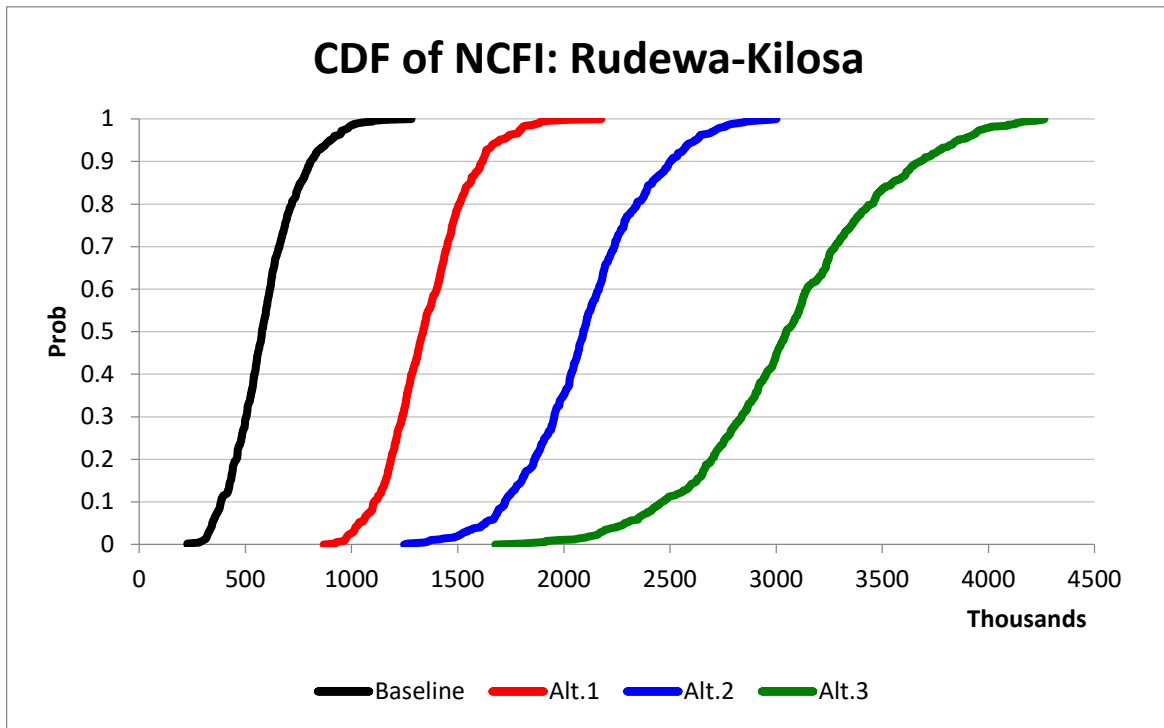


Figure 25a. Cumulative distribution function of the NCFI for Rudewa-Mbuyuni village

The Stoplight chart in figure 25b illustrates NCFI in year three of the five-year planning horizon for the baseline and three alternative scenarios. In the baseline scenario, there is a 68% chance that NCFI will be less than 650,000 TSh and a 0% chance that NCFI will exceed 2,100,000 TSh. In contrast, farmers that adopt the SRI system in combination with irrigated dry-season crops and increased fertilization rates for maize (Alts. 2 and 3) have a 49% and 98% probability, respectively, of generating NCFI of more than 2,100,000 TSh. A farmer that cultivates rain-fed rice in combination with irrigated dry-season crops and increased fertilization rates for maize (Alt. 1) has a 100% chance of generating NCFI between 650,000 and 2,100,000 TSh for year three of the five-year planning horizon.

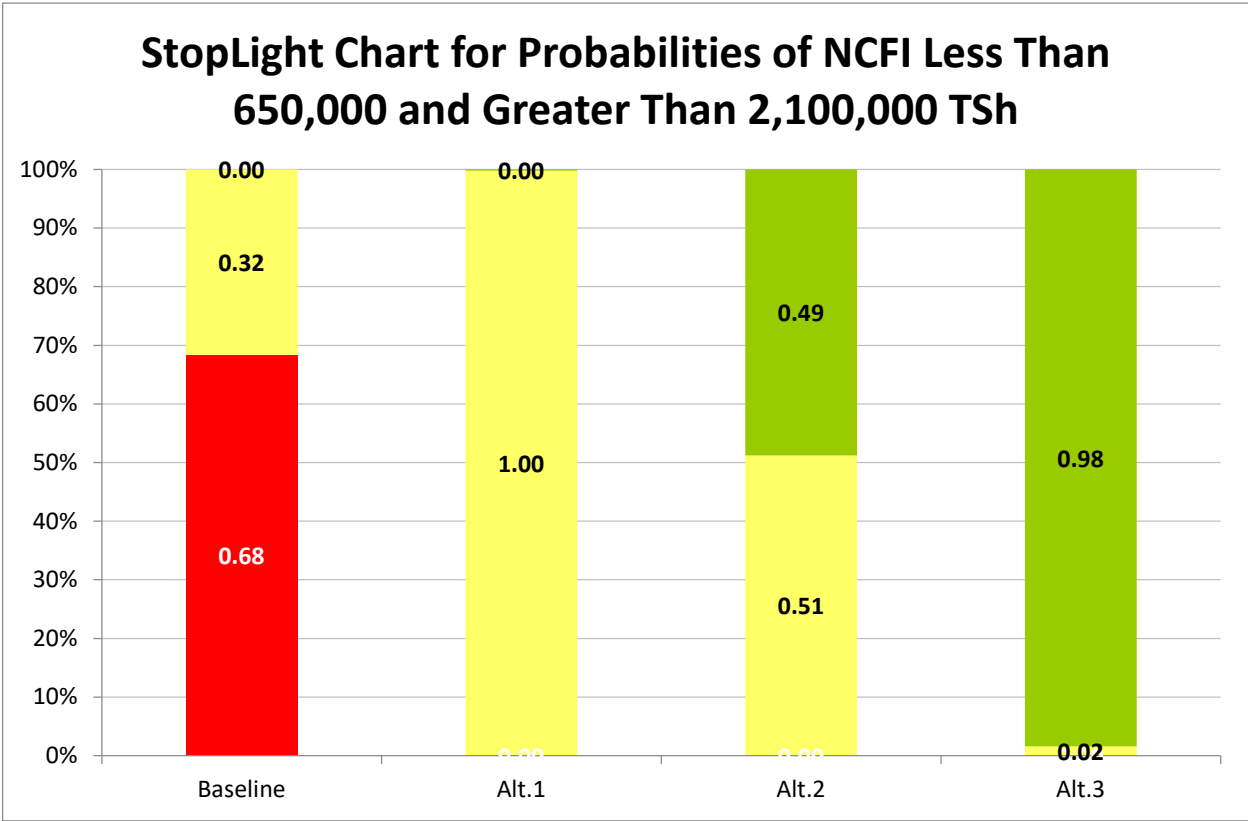


Figure 25b. StopLight chart of the NCFI for Rudewa-Mbuyuni village

4.4.3 EC. Figure 26a illustrates potential EC in the fifth year of the five-year planning horizon. Once again, the scenarios adopting the SRI method for rice cultivation (Alts. 2 and 3) significantly outperform the baseline scenario 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. Farmers who grow rain-fed rice in combination with irrigated dry-season crops and increased fertilization rates for maize (Alt. 1) have higher EC than farmers under the baseline scenario.

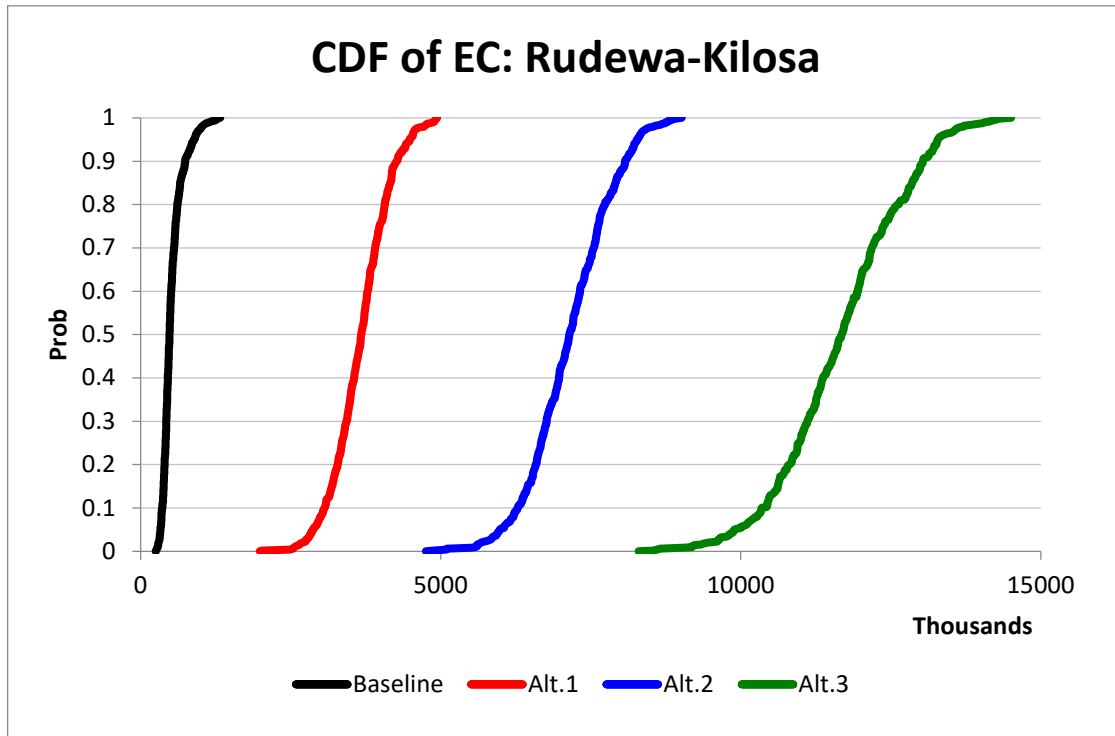


Figure 26a. Cumulative distribution function of the ending cash reserves for Rudewa-Mbuyuni village

For farmers that apply increased irrigation, fertilizers, and the SRI method for rice cultivation (Alts. 2 and 3), there is a 58% and 100% probability, respectively, that EC in year five will exceed 7,000,000 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 irrigated dry-season crops and increased fertilization rates for maize (Alt. 1) have a 100% chance of generating EC of more than 700,000 TSh but less than 7,000,000 TSh. For a farmer in the baseline scenario, there is an 87% probability of that EC will be less than 700,000 TSh in year five (fig. 26b).

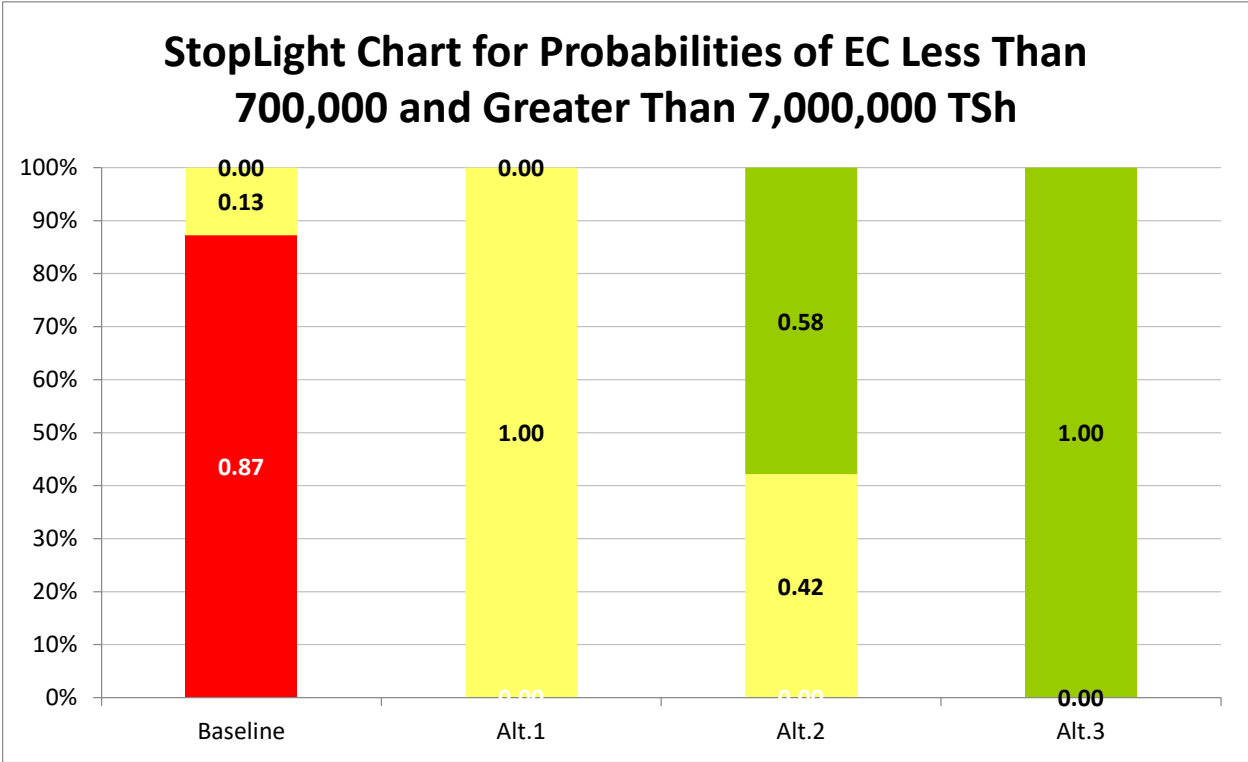


Figure 26b. StopLight chart of the ending cash reserves for Rudewa Mbuyuni village

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 Rudewa Mbuyuni village, in the Kilosa 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 Kilosa, 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 Rudewa watershed. Cropland comprises a very small percentage (just 1.46%) of total land in the watershed; even when combined with irrigable pasture land, the area to be irrigated would comprise just 1.74% of total land in the watershed. Accordingly, the total annual volume of irrigation water withdrawn in the watershed would be less than 960,000 m³, or just 0.14% of the annual stream flow leaving the watershed. Moreover, simulations indicated that proposed SSI interventions would reduce average monthly stream flow by only 0.69%. Though peak river flows during the wet season and moderate flows during the dry season would be unaffected by SSI, very low river flows during the dry season would be significantly affected by the withdrawal of irrigation water from rivers. This suggests that the proposed SSI interventions are sustainable, and would not compromise the overall environmental health of the watershed, though some alternative surface water storage or groundwater extraction may be needed to supply human and livestock drinking water when the very low flows may be reduced. Moreover, 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. The implementation of multiple cropping systems also affected simulated crop yields. Proper understanding and use of multiple cropping combinations could increase crop yields and improve soil health, but some combinations if under-fertilized would probably decrease productivity. For the fertilizer application scenarios simulated in this study, simulations indicated a significant increase in rice yield for each of the multiple cropping scenarios, with the highest rice yield resulting from multiple cropping of rice with fodder. Multiple cropping of maize with fodder significantly increased simulated maize yield, whereas multiple cropping of maize with cabbage decreased simulated maize yield slightly. Tomato and fodder yields decreased significantly when simulated as multiple crops with rain-fed rice and maize. Cabbage yields also decreased slightly in both multiple cropping scenarios. These reductions in simulated yields generally reflected increases in nitrogen stress to the affected crops, and suggest the need for further exploration of appropriate fertilization amounts for these particular multiple cropping combinations.

Simulations 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 Rudewa-Mbuyuni, a village in Kilosa. The scenarios that implemented continuous cropping of SRI rice, improved fertilization rates for maize, and multiple cropping of the rainy-season, fertilized maize crop with irrigated, dry-season vegetables and fodder, 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). Cash income increased as the irrigated area increased. The most preferred scenario in terms of income generation was the one that allocated the largest area of irrigable cropland to vegetables, fodder and SRI rice.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies (in Vitamin A particularly) 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 extremely modest percentages of cropland and irrigable pasture land in the area (together, just 1.74% of total land in the watershed) also limit the expansion of SSI and cultivation of additional crops in the Rudewa 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	11/15	
Tillage	10/30	Tillage	11/30	
Planting	10/30	DAP fertilizer application	11/30	25 kg
Harvest	2/20	Transplanting	11/30	
		1st stage urea fertilizer application	11/30	50 kg
		2nd stage urea fertilizer application	2/28	50 kg
		Harvest	4/9	

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

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

Rice rainy season	Date	Amounts/ remark	Rice dry season	Date	Amounts/ remark
Tillage	11/15		Tillage	4/30	
Tillage	11/30		Tillage	5/15	
1st stage urea fertilizer application	11/30	50 kg/ha	1st stage urea fertilizer application	5/15	50 kg/ha
Transplanting	11/30		Transplanting	5/15	
DAP fertilizer application	11/30	25 kg/ha	DAP fertilizer application	5/15	25 kg/ha
2nd stage urea fertilizer application	2/28	50 kg/ha	2nd stage urea fertilizer application	8/13	50 kg/ha
Harvest	4/9		Harvest	9/23	

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

Maize rainy season	Dates	Tomato dry season	Dates	Amount/remark
Tillage	10/10	Tillage	4/30	
Tillage	10/30	Tillage	5/15	
1st stage urea fertilizer application	25 kg/ha	1st stage urea fertilizer application	5/15	34 kg/ha
DAP fertilizer application	50 kg/ha	Transplanting	5/15	
Planting	10/30	Harvest	7/30	
2nd stage urea fertilizer application	25 kg/ha			
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.

d) First year Napier grass management

Year	Date	Practice	Amount
1	5-Nov	Tillage	
	1-Dec	Tillage	
	1-Dec	Planting	
	1-Dec	DAP	100 kg/ha
	28-Feb	Harvest	
	1-Mar	Urea	20 kg/ha
	30-Apr	Harvest	
	1-May	Urea	20 kg/ha
	15-Jul	Harvest	
	16-Jul	Urea	20 kg/ha
	30-Sep	Harvest	
	1-Oct	Urea	20 kg/ha
	15-Dec	Harvest	
	16-Dec	Urea	20 kg/ha

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**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfed Maize	■	■	■								■	■
Rainfed Rice	■	■	■	■								■
Irrigated Tomato					■	■	■	■	■			
Irrigated Cabbage					■	■	■	■	■			
Irrigated Fodder (oats + Vetch)						■	■	■	■			
Maize + Irr - Tomato	■	■			■	■	■	■	■		■	■
Maize + Irr - Cabbage	■	■			■	■	■	■	■		■	■
Maize + Irr - Fodder	■	■				■	■	■	■		■	■
Fert - Maize + Irr - Tomato	■	■			■	■	■	■	■		■	■
Fert - Maize + Irr - Cabbage	■	■			■	■	■	■	■		■	■
Fert - Maize + Irr - Fodder	■	■				■	■	■	■		■	■
Rice + Irr - Tomato	■	■	■	■		■	■	■	■			■
Rice + Irr - Cabbage	■	■	■	■		■	■	■	■			■
Rice + Irr - Fodder	■	■	■	■		■	■	■	■			■
Alfalfa	■	■	■	■	■	■	■	■	■	■	■	■
Napier grass	■	■	■	■	■	■	■	■	■	■	■	■
SRI Rice			■	■	■	■	■	■	■			

Where: Irr and Fert are irrigation and fertilizer 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 yr	Tillage	6/30	
1st yr	Tillage	7/10	
1st yr	Tillage	7/20	
1st yr	DAP fertilizer application	7/20 (100 kg/ha)	One time only (First year)
1st yr	Planting	7/20	
2nd yr	1st Cut	3/16	First cut after 8 months
2nd yr	Urea fertilizer application	3/17 (50kg/ha)	Every 60 days
2nd yr	Cut	5/15	Harvest every 60 days
2nd yr	Urea fertilizer application	5/16 (50kg/ha)	Every 60 days
2nd yr	Cut	7/14	Harvest every 60 days
2nd yr	Urea fertilizer application	7/15 (50kg/ha)	Every 60 days
2nd yr	DAP fertilizer application	7/15 (50 kg/ha)	Once every year from 2nd -5th
2nd yr	Cut	9/12	
2nd yr	Urea fertilizer application	9/13 (50kg/ha)	Every 60 days
2nd yr	Cut	11/11	
2nd yr	Urea fertilizer application	11/12 (50kg/ha)	Every 60 days
3rd year	Cut	1/10	
2nd yr	Urea fertilizer application	1/11 (50kg/ha)	Every 60 days
3rd year	Cut	3/11	
Cut every 60 days, 50kg/ha urea every 60 days following the cut and 50 kg/ha of DAP every year			
5th year	Harvest	7/1 5 yr	Harvest
5th year	Kill and replant	7/2 After 5 yr	Kill and replant

f). Napier grass schedule

	Operations	Date	Notes
1st yr	Tillage	7/5	
1st yr	Tillage	7/20	
1st yr	DAP fertilizer application	7/20 (100 kg/ha)	One time only (First year)
1st yr	Planting	7/20	
2nd yr	1st Cut	1/16	First cut after 6 months
2nd yr	UREA fertilizer application	1/16 (50 kg/ha)	
2nd yr	Next Cut	7/17	
2nd yr	UREA fertilizer application	7/17 (50 kg/ha)	
3rd year	Harvest	After 3 yr	Final cut and replant

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