FEED THE FUTURE
The U.S. Government's Global Hunger & Food Security Initiative

Small-Scale Irrigation Applications for Smallholder Farmers in Ghana
Ex Ante Analysis of Options

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

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Introduction

The research reported here 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 at three target sites in Ghana. ILSSI was formed to undertake research aimed at increasing food production, improving nutrition, accelerating economic development, and contributing to the protection of the environment in Ethiopia, Tanzania and Ghana. We are currently working to generate actionable recommendations for strategic investments in agricultural development in rural Ghana by integrating: natural resources, agricultural, and socioeconomic data; input from local farm families; local agronomic research and demonstrations; and powerful natural resource, agronomic, and farm-scale economic models. We are also training local government agency personnel and university faculty and students to continue using ILSSI tools and methodologies to inform national decision makers after this five-year project is completed.

ILSSI combines: the on-site agronomic and SSI expertise of the International Water Management Institute (IWMI), the International Livestock Research Institute (ILRI), and North Carolina A&T State University (NCAT); the socioeconomic research capabilities of the International Food Policy Research Institute (IFPRI); and the hydrologic, agronomic, and farm-scale economic modeling experience of Texas A&M University (TAMU). The project requires close interaction with international, national, and local agriculture and rural development professionals; local farm families and community leaders; and university faculty and students engaged in agricultural and rural development research in the target regions. IWMI and ILRI have facilitated close working relations with these stakeholders in support of ILSSI activities.

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

This report deals with the third ILSSI component, using ILSSI's Integrated Decision Support System (IDSS) to quantitatively estimate the impacts of proposed SSI interventions. 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 and long-term changes in crop and livestock production, farm economies, and environmental services produced by changing land uses, agricultural technologies and policies, climate, and water resources management (including SSI). The three models (and their sister and antecedent decision tools) have been used successfully for more than 25 years to address complex biophysical and economic issues in the United States and around the world, providing decision makers with reliable predictions of the production, environmental, and economic impacts of their actions. A detailed description of the IDSS is found in Appendix 1.

In the ILSSI studies, the IDSS analyses are used to: (1) evaluate results of field studies; (2) produce quantitative stochastic integrated estimates of outcomes and impacts of the interventions; (3) seek optimal combinations of inputs for best use of interventions; (4) assess upstream, downstream, and community-level implications of the interventions; (5) provide input to training and educational materials for use at local and higher administrative levels; (6) scale up the estimates of production, environmental, and economic consequences of the interventions to geographically equivalent areas of the country; and (7) provide policy makers and private sector investors with scaled-up inputs that contribute to decisions on future investments.

Figure 1 shows the shows the results framework involving information and analysis flow of the IDSS: from definition of scenarios for analysis; through interaction of model components to create ex ante and ex post analyses; leading to users and ultimate adoption and application of SSI technologies. An overview of the results of IDSS ex ante analyses of proposed SSI interventions in Ghana is provided in the following section ("Summary of Results for Ghana"). More detailed summaries of the proposed SSI interventions and ex ante analyses at each of the three target sites, including actionable recommendations regarding proposed SSI interventions, are included in the subsequent section ("Regional Summaries").

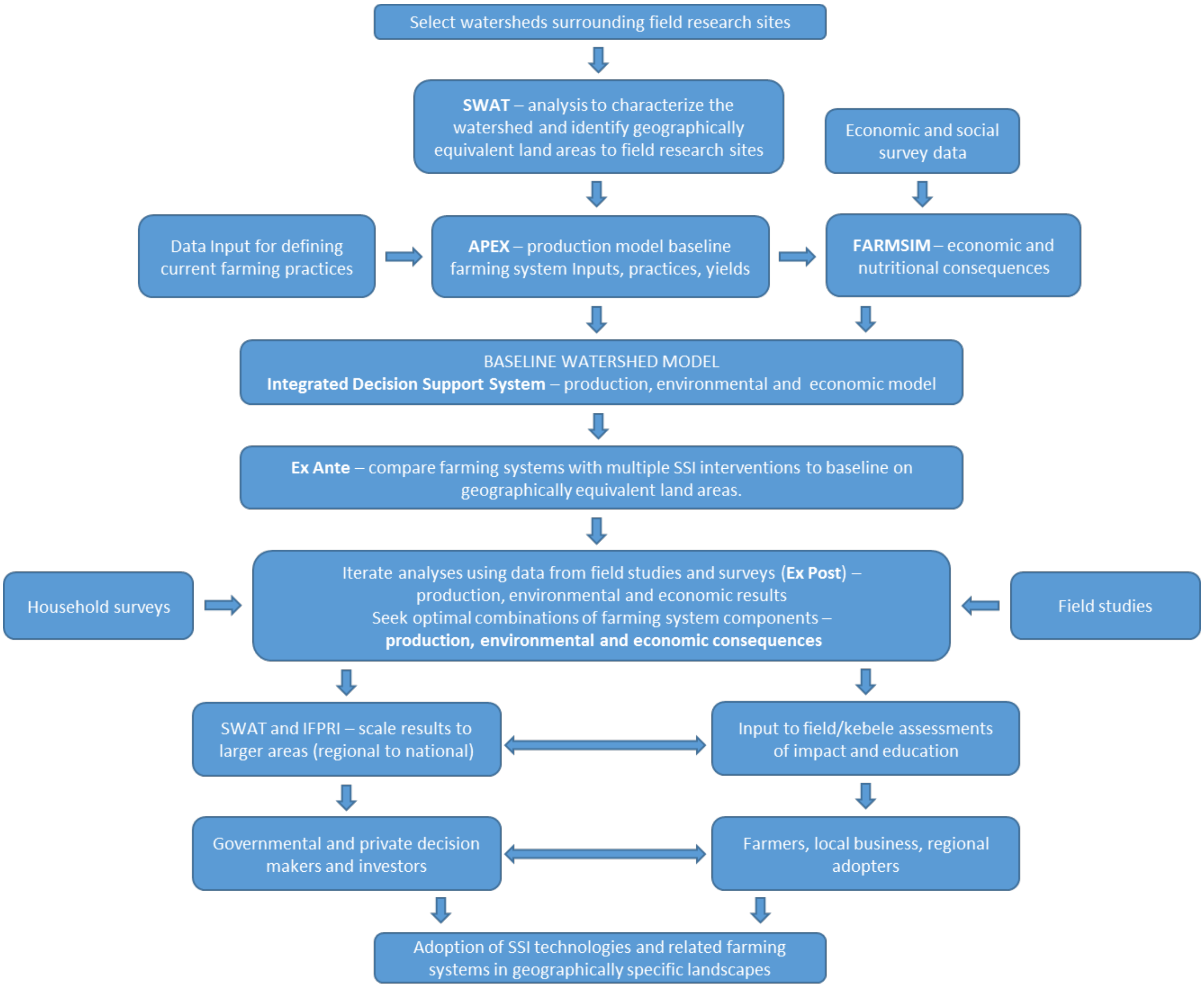
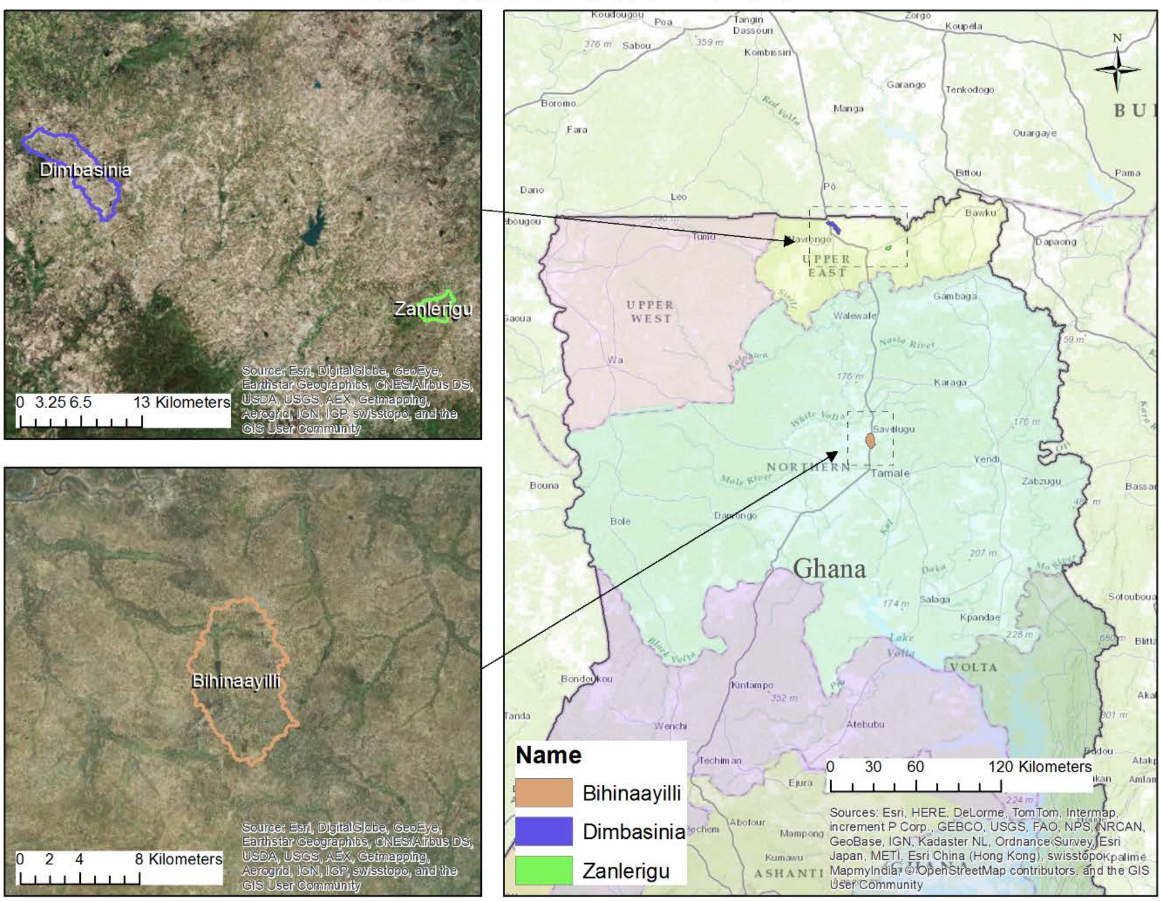


Figure 1. Results framework: information and analysis flow of the IDSS

Summary of Results for Ghana

ILSSI analyzed proposed SSI interventions in watersheds located in three different watersheds/districts in the Republic of Ghana: the Bihinaayili watershed, located in the Savelugu-Nanton District in the Northern Region; the Nimbasinia (or Dambiasinia/Dimbasinia) watershed, located in the Kassena Nankana District in the Upper East Region; and the Zanlerigu watershed, located in the Nabdam District, also in the Upper East Region. Though crops and management practices vary somewhat from region to region, farm-family livelihoods for all of the target sites are derived from grains and other main crops, like soybean, produced in the rainy season. Vegetables such as tomato and pepper are produced as well, and cultivation of these crops could be expanded with the implementation of SSI in the dry season; however, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

ILSSI Research Sites in Ghana



In each of the three target sites, ILSSI proposed implementing SSI (using irrigation water from either shallow groundwater or water-harvesting ponds, depending on the site) to maximize cultivation of high-value vegetable and fodder crops in the dry season. ILSSI evaluated the impacts of the proposed SSI interventions at each of the three target sites by simulating and comparing current and alternative farming systems specific to each site.

For each site, all three ILSSI component models were used in an interactive and integrated fashion. SWAT was used to simulate watershed-scale hydrology and soil erosion to examine the effects of the proposed SSI interventions. APEX was used to analyze the impacts of the proposed SSI interventions on crop yields and soil erosion at the field scale. FARMSIM was used to determine the effects of the proposed SSI interventions on farm family livelihoods and nutrition. Stakeholders have been engaged throughout the project through: interactions with ILSSI in-country staff; surveys of farm-family resources, practices and needs; and informal training and short courses for in-country university faculty, students, and government officials.

Simulations with the integrated and interactive IDSS models allowed us to evaluate:

- the land appropriate for SSI of dry-season crops at each of the three sites;
- the amount of irrigation water required for the proposed SSI interventions at each of the three sites;
- the complete hydrology of each watershed (e.g, groundwater recharge and runoff rates) with and without the proposed SSI interventions;
- soil erosion rates associated with current cropping systems and the proposed SSI interventions;
- the impacts of various farming practices (e.g., current versus recommended fertilization rates) on crop yields, watershed hydrology, and farm economies, when implemented in conjunction with the proposed SSI interventions; and
- the economic and nutritional benefits to typical farm families of implementing the proposed SSI interventions.

In the Bihinaayili watershed, water-harvesting ponds along the stream networks (used to collect and store overflow from the nearby Ligba dam) served as the source of irrigation water. Simulations indicated that there would be ample water available in the watershed for the proposed SSI interventions; however, the proposed SSI interventions would reduce average monthly stream flow by 37%, reduce peak flows, and increase low flows. A decrease in peak flows (and a related reduction in sediment influxes) and an increase in low flows could have positive implications for upstream and downstream social and ecological systems; however, a decrease in average monthly stream flows could have negative impacts on downstream social-ecological systems. Moreover, the dugouts will be susceptible to siltation, and dredging sediment loads from the dugouts to the fields will be a challenging task. The exact upstream and downstream costs and benefits, both social and environmental, of the proposed SSI interventions in Bihinaayili, as well as potential methods of addressing sedimentation of dugouts, could be addressed in future research.

The proposed SSI interventions in the Nimbasinia and Zanlerigu watersheds relied on shallow groundwater as the source of irrigation water. There is large water resources potential in both watersheds; however, at both of these sites, the annual irrigation water requirements for cultivation of selected dry-season crops exceeded the average annual shallow groundwater recharge. Implementation of the proposed SSI interventions also caused modest reductions in the monthly stream flows in the two watersheds, and reductions in peak and low flows.

Accordingly, in the Nimbasinia and Zanlerigu watersheds, we recommend combining irrigation from the shallow groundwater aquifers with irrigation from other water sources. For example, water-harvesting ponds such as those used in Bihinaayili could be used to store and capture surface runoff for SSI. We also recommend selecting water-efficient crops for dry-season cultivation in order to minimize reductions in stream flows. Analyses of potential dugout sites and scale, likely costs and benefits of irrigating from dugouts, and recommendations as to specific water-efficient crops for cultivation, were beyond the scope of this study but could be addressed in future research.

Simulations of crop yields in the alternative scenarios showed that the application of additional fertilizers would increase crop yields substantially at each of the three sites. The implementation of multiple-cropping systems also affected simulated crop yields at each of the three sites. At all three sites, multiple cropping of the rainy-season grain crops with fodder significantly increased simulated grain yields by increasing residual nitrogen, without adversely affecting fodder yields. At all three sites, multiple cropping of the rainy-season grain crops with tomato also increased simulated grain yields (although by lesser amounts), but significantly reduced tomato yields. In Bihinaayili, multiple cropping of soybean with dry-season crops did not significantly affect simulated yields of soybean or the dry-season crops. In Zanlerigu, high temperature stress was also a major factor limiting yields of certain crops. For example, the yield of pepper planted as a rain-fed crop in the cooler season was double that of irrigated, dry-season pepper. Planting temperature-sensitive crops (like pepper and oats) in the cooler season would therefore also optimize yields.

Simulations of flow and sediment indicated that the proposed SSI interventions in Nimbasinia and Zanlerigu would not significantly affect runoff and sediment yields. In Bihinaayili, however, multiple cropping of sorghum (at both current and improved fertilization rates) with fodder and pepper increased sediment yields by between 20% and 26%.

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 communities in each of the three watersheds. In the Bihinaayili community, simulation results indicated that multiple cropping of dry-season crops with soybean was far more profitable than multiple-cropping of dry-season crops with maize. Similarly, in the Nimbasinia community, the scenarios that implemented multiple cropping of the dry-season crops with sorghum (rather than maize) were preferable. Multiple-cropping with maize and millet were found to be equally profitable in the Zanlerigu community.

The simulations also compared the costs and benefits of three alternative water-lifting technologies: pulley-and-bucket irrigation; diesel-pump (both rented and owned) irrigation; and solar-pump irrigation. At all three sites, the scenarios that implemented multiple cropping of the preferred rainy-season crop(s) with diesel- and solar-pump-irrigated dry-season crops produced by far the highest net present value, net cash farm income, and ending cash reserves of the scenarios simulated (including the non-irrigated and pulley-irrigated scenarios). Additionally, in light of the lower maintenance and environmental costs of solar pumps, simulations at all three sites suggested that investments in solar water-lifting technologies would pay dividends in the long run.

Despite substantial improvements in farm family economics resulting from the proposed SSI interventions, at all three sites, the levels of certain nutrients remained at merely adequate levels, and a nutritional deficiency in iron persisted under the simulated, improved cropping system in Bihinaayili. We would therefore propose expanding the types of irrigated, dry-season crops at all three sites to further increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits.

As noted above, the results of our analysis raise a number of issues to be resolved in future modeling and field research. These include the need to identify:

- exact upstream and downstream costs and benefits (both social and environmental) of decreases in average stream flows and peak flows, as well as increases in low flows;
- potential methods of addressing sedimentation of water-harvesting ponds where utilized;
- the potential scale and locations, as well as the costs and benefits, of water-harvesting ponds or structures to supplement shallow-groundwater irrigation in Nimbasinia and Zanlerigu; and
- recommendations as to specific water-efficient crops for cultivation

The evaluation and comparison of these and other issues, 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.

ILSSI plans to continue engaging with local leaders, university faculty and students, and government officials, to test the results of ex ante analyses and examine other SSI and farming system alternatives suggested by local farmers and other agricultural experts. We anticipate and recommend that in-country research on the applicability of SSI be informed by and respond to the ex ante analyses summarized above and discussed in further detail below. The ILSSI modeling team stands ready to complement field and simulation studies conducted by in-country collaborators, continually improving our ability to accurately represent the production, environmental, and economic effects of SSI and related agricultural practices.

Regional Summaries:
Interpretive Summaries of Ex Ante Analyses of Regional SSI Interventions

ILSSI completed ex ante analyses of the consequences of SSI interventions at three different sites in Ghana: the Bihinaayili watershed in the Northern Region; and the Nimbasinia and Zanlerigu watersheds, both in the Upper East Region. Detailed reports of these ex ante analyses are prepared as stand-alone documents and are attached to this report. The following are interpretive summaries of these more comprehensive reports.

<u>Bihinaayili</u>

The Bihinaayili watershed is located in the Savelugu-Nanton District in the Northern Region of Ghana. The annual crops yields produced in the area are far below global average yields. Farm-family livelihoods are derived from main crops, such as maize, sorghum, and soybean, produced in the rainy season. Vegetables such as tomato and pepper are produced as well, and cultivation of these crops could be expanded with the implementation of SSI in the dry season.

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

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

For purposes of the simulations, APEX and FARMSIM chose tomato, pepper and fodder (oats/vetch) as representative irrigated dry-season crops, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications.

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

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

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

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies in iron persisted under the simulated, improved cropping systems. We would also, therefore, propose expanding the types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits.

Further evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future simulation and field research.

Nimbasinia

The Nimbasinia (or Dambiasinia/Dimbasinia) watershed is located in the Kassena Nankana District in Upper East Region of Ghana. The annual crops yields produced in the area are far below global average yields. Farm-family livelihoods are derived from main crops, such as maize and sorghum, produced in the rainy season. Vegetables such as tomato and pepper are produced as well, and cultivation of these crops could be expanded with the implementation of SSI in the dry season; however, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

In Nimbasinia, ILSSI proposed implementing SSI, using shallow groundwater and one of three alternative water-lifting technologies, to maximize cultivation of high-value vegetable and fodder crops in the dry season. ILSSI evaluated the proposed SSI interventions by simulating and comparing two alternative farming systems:

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

For purposes of the simulations, APEX and FARMSIM chose tomato, pepper and fodder (oats/vetch) as representative irrigated dry-season crops, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications.

Simulations of watershed-scale hydrology indicated that there is large water resources potential in the Nimbasinia watershed. The total annual groundwater recharge was more than 147 mm, and the annual generated surface runoff was more than 45 mm. However, the average annual irrigation water requirement for cultivating dry-season pepper and Napier grass exceeded the average annual shallow groundwater recharge. Implementation of SSI for dry-season pepper and Napier grass production caused a modest reduction in the monthly stream flow. Peak flows and low flows also decreased with implementation of the irrigated pepper/Napier grass scenario.

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

Simulations of flow, sediment, and crop yields in the alternative scenarios showed that the application of additional fertilizers would increase crop yields substantially without a considerable impact on the environment. More specifically, the addition of 50 kg/ha of urea and 50 kg/ha of DAP doubled simulated maize and sorghum yields and did not significantly affect runoff and sediment yields. Proper understanding and use of multiple-cropping combinations could also increase crop yields and improve soil health, although some combinations with under-fertilization would probably decrease productivity. For the fertilizer application scenarios simulated in this study, multiple cropping of maize or sorghum with fodder (oats/vetch) doubled simulated maize and sorghum yields by increasing residual nitrogen, and did not adversely affect fodder yields. Multiple cropping of the grain crops with pepper and tomato also increased simulated maize and sorghum yields, although by lesser amounts, and did not significantly affect pepper yields; tomato yield decreased, however, with multiple cropping.

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 Nimbasinia village. These simulations also compared the costs and benefits of three alternative water-lifting technologies: pulley-and-bucket irrigation; diesel-pump (both rented and owned) irrigation; and solar-pump irrigation. In all, six scenarios (including the baseline, non-irrigated scenario) were simulated. The scenarios that implemented multiple cropping of sorghum (rather than maize) with diesel- and solar-pump-irrigated dry-season crops produced by far the highest net present value, net cash farm income, and ending cash reserves of the scenarios simulated (including the baseline, non-irrigated scenario). In contrast, the scenarios that included multiple cropping of maize with diesel-pump-irrigated dry-season crops and multiple cropping of sorghum with pulley-irrigated dry-season crops did not differ greatly from the baseline, non-irrigated scenario.

The simulated, improved cropping systems resulted in significant improvements in farm-family nutrition. While levels of calories, protein, fat, calcium, iron, and vitamin A were all deficient in the baseline, non-irrigated scenario, in the alternative scenarios, levels of calories, protein, and fat met and even exceeded daily requirements, and levels of calcium, iron, and vitamin A were adequate. We would propose expanding the types of crops irrigated in the dry season to further increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits.

The evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future simulation and field research.

Zanlerigu

The Zanlerigu watershed is located in the Nabdam District in the Upper East Region of Ghana. The annual crops yields produced in the area are far below global average yields. Farm-family livelihoods are derived from main crops, such as maize and millet, produced in the rainy season. Vegetables such as tomato and red pepper are produced as well, and cultivation of these crops could be expanded with the implementation of SSI in the dry season; however, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

In Zanlerigu, ILSSI proposed implementing SSI, using shallow groundwater and one of three alternative water-lifting technologies, to maximize cultivation of high-value vegetable and fodder crops in the dry season. ILSSI evaluated the proposed SSI interventions by simulating and comparing two alternative farming systems:

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

For purposes of the simulations, APEX and FARMSIM chose tomato, pepper and fodder (oats/vetch) as representative irrigated dry-season crops, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications.

Simulations of watershed-scale hydrology indicated that there is large water resources potential in the Zanlerigu watershed. The total annual groundwater recharge was more than 112 mm, and the annual generated surface runoff was more than 73 mm. However, the average annual irrigation water requirement for cultivating dry-season pepper and Napier grass exceeded the average annual shallow groundwater recharge. Implementation of SSI for dry-season pepper and Napier grass production caused a modest reduction in the monthly stream flow. Peak flows and low flows also decreased with implementation of the irrigated pepper/Napier grass scenario.

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

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

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping systems) on farm-family economics in Zanlerigu village. These simulations also compared the costs and benefits of three alternative water-lifting technologies: pulley-and-bucket irrigation; diesel-pump (both rented and owned) irrigation; and solar-pump irrigation. In all, five scenarios (including the baseline, non-irrigated scenario) were simulated. The pulley-irrigated, multiple-cropping scenario did not differ greatly from the baseline, non-irrigated scenario. In contrast, the scenarios that implemented multiple cropping of grain crops with diesel- and solar-pump-irrigated dry-season crops produced by far the highest net present value, net cash farm income, and ending cash reserves of the scenarios simulated (including the baseline, non-irrigated scenario). Given the lower maintenance and environmental costs of solar pumps, simulation results suggest that investments in solar water-lifting technologies will pay dividends in the long run.

The simulated, improved cropping systems resulted in improvements in farm-family nutrition. While levels of fat were deficient and levels of calcium, iron, and vitamin A were merely adequate in the baseline, non-irrigated scenario, in the alternative scenarios, levels of fat and vitamin A exceeded daily requirements (though levels of calcium and iron remained at only adequate levels). We would propose expanding the types of crops irrigated in the dry season to further increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits.

The evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future simulation and field research.

Appendix 1

WHAT IS AN "INTEGRATED" DECISION SUPPORT SYSTEM?

Agricultural ecosystems are complex. At the farm level, their performance is influenced by a myriad of biophysical and socioeconomic factors, including: weather, soil properties, land forms, land uses, crop and livestock management practices, farm sizes and financial resources, farmer experience and labor availability, farmer financial and equipment resources, farm family needs, input and output prices, and availability of credit. At larger scales, such as watersheds and regional political subdivisions, the larger environmental and socioeconomic effects of agriculture on natural resources, environmental services, community wellbeing, and local/regional markets may become significant. The complex and interactive effects of these factors on farm productivity and economics, as well as local ecosystem services, make agricultural decision making difficult --- both for farm families and policy makers.

In recognition of these complexities, the Integrated Decision Support System (IDSS) has been created to "integrate" the interactions of crop and livestock production, environmental conditions, and farm family economics into the decision making process. IDSS analyses are meant to address farm-level as well as watershed and larger-scale impacts. Thus, decision makers with access to IDSS analyses will have a more complete understanding of the likely effects of their decisions on food production, natural resources, environmental services, and economics --- both at the farm and larger scales.

IDSS Tools.
The IDSS (http://IDSS.tamu.edu) includes a suite of spatially explicit simulation models that include: SWAT- Soil and Water Assessment Tool (http://swat.tamu.edu), APEX-Agricultural Policy Environmental eXtender (http://epicapex.tamu.edu), and FARMSIM-Farm Income and Nutrition Simulator (http://afpc.tamu.edu). The complete IDSS package also includes a wide variety of biophysical and socioeconomic databases characterizing the biophysical, economic, and management factors affecting the agroecosystem. A series of graphical and statistical tools are also provided to IDSS users to help them analyze and visualize both the inputs and outputs of analyses.

These IDSS models have been extensively used across the U.S. and in international settings to analyze the performance of many diverse agroecosystems at the farm, watershed, and larger scales. Collectively they provide an integrated approach linking production, economic, and environmental consequences of agricultural systems, new technology, and farm policy, for decision makers at multiple temporal and spatial scales. The biophysical databases used by the IDSS are largely available worldwide in the form of geographic information systems (GIS) and other natural resources databases. The crop management and economic inputs are largely obtained locally from agricultural experts familiar with local management practices and farm family and market surveys.

IDSS developers and users are well aware of the complexities of modeling complex agroecosystems. As a result, capacity building is an important goal of the ILSSI project. Short courses designed to increase the analytical and decision skills of IDSS users are offered to university students and agricultural professionals in all three ILSSI countries on a regular basis. The IDSS team includes scientists with deep professional understanding of African ecosystems to provide guidance to African users.

Finally, the IDSS "team" includes representatives of international agricultural research organizations (IWMI and ILRI) and faculty at several African universities. These colleagues maintain close working relationships with government agencies, non-governmental development organizations, and local farmer and community groups. As part of the ILSSI project, they conduct field research on issues related to small-scale irrigation and provide these data to the IDSS modeling team for use in model calibration and verification. This linkage is critical not only to obtain information about current agricultural practices, but also to conduct real-world evaluations and demonstrations of new small-scale irrigation technologies. Figure 1 shows the major components and information flows with the IDSS.

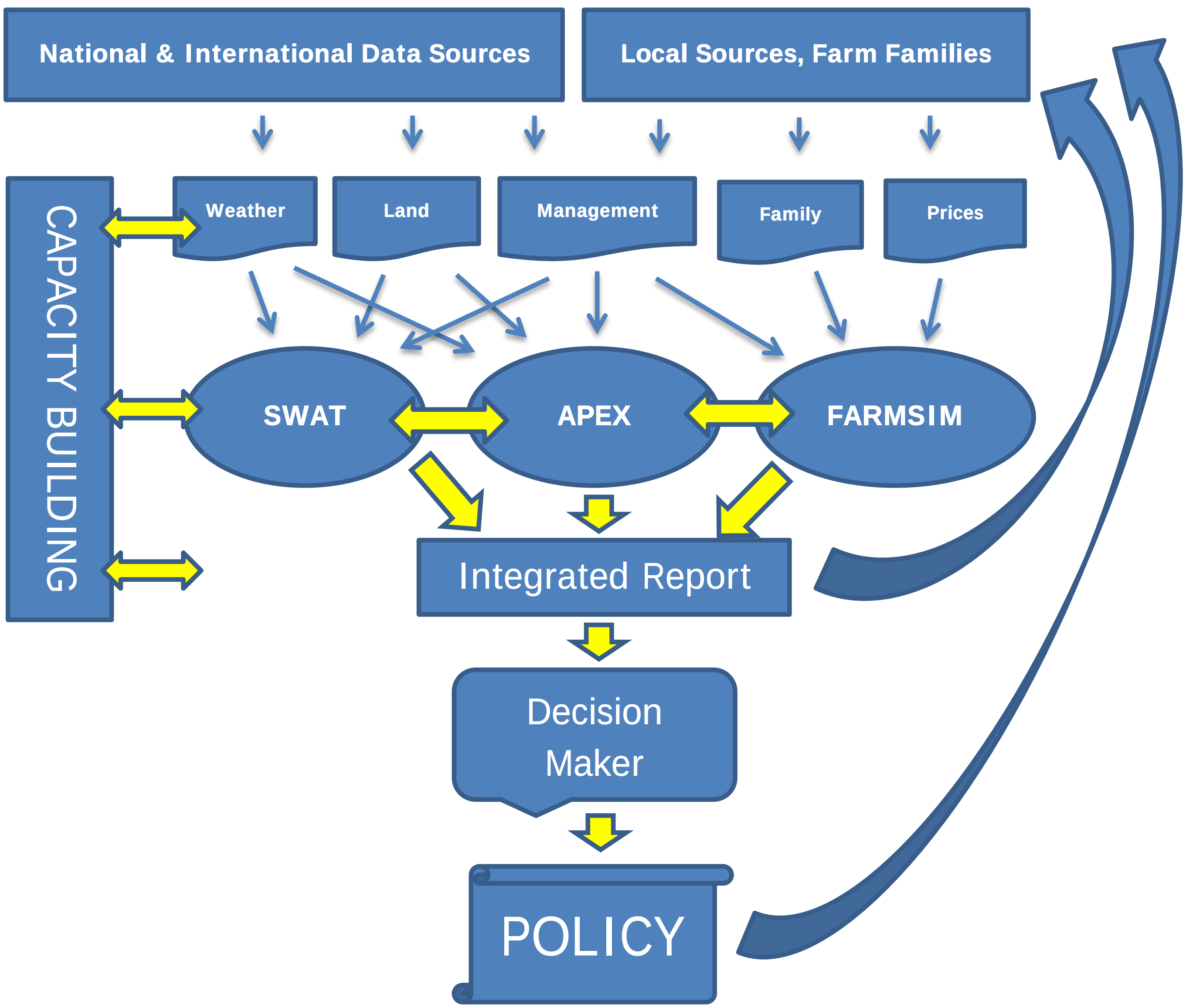


Figure 1. Information flows within the IDSS.