Participatory approach for model-based decision support system development with Ugandan smallholder farmers

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Contents

Executive Summary

The purposes of this project were to carry out preliminary work in (1) adapting an established crop-production and hydrologic model in the context of Ugandan smallholder agriculture, and (2) identifying farmers' concerns and issues that might be addressed collaboratively through the implementation of model-based decision-support tools. This paper summarizes initial approaches in the technical setup of the model, and in exploring methodological issues in involving rural Ugandan farmers as stakeholders in model-based research. I use insights from model setup and configuration and semi-structured interviews with farmers in Uganda to propose a generalized approach for collaborating with rural communities in model-based agricultural development research projects. My involvement with the organizations and communities discussed here continues to the present, and I intend to use the lessons from this project to inform continued work in Uganda as part of my PhD with the Geography Graduate Group at UC Davis.

Background

Decision-making is an important issue in farm management that has caught the attention of development NGOs and researchers alike. In Uganda, most rural farmers make difficult decisions about whether and how to invest limited resources within their farm-household systems, and are highly affected by constraints on critical components like water or agricultural inputs (Enfors and Gordon, 2008; Gordon et al., 2010; Suich et al., 2015; O'Connor, 2001). With incomes and subsistence contingent on a complex set of agricultural, climate, political, and economic dynamics, rural agricultural communities in Uganda and elsewhere in sub-Saharan Africa live within "one of the most precarious livelihood systems in the world" (Devereux, 2009).

Decision-support tools derived from agricultural, ecological, and economic system models are designed to assist in navigating constraints and tradeoffs faced by farmers by presenting clear decision stages and outcomes of hypothetical scenarios (Rose et al., 2016). Models and decision-support systems have been built for a wide range of issues, including farm sustainability (e.g. Lewis and Bardon, 1998), manure management (e.g. Karmakar et al., 2007), crop production (e.g. Jones et al., 2003; Jones, 1993), and many others (Van Meensel et al., 2012). In the Global North such models are frequently used by researchers to integrate and extend current knowledge, and for informing policy analysis and large-scale land and resource management decisions (Parker et al., 2004).

Despite acknowledgement of their potential for clarifying complex systems management and policy options, applications of similar modeling and decision-support tools for agriculture in the Global South are more rare, and face different challenges (McCown et al., 1994). These include the difficulty of sufficiently capturing the complexity of smallholder agricultural systems, poor quality or small quantities of data, technical challenges in downscaling of models to be relevant to local-level planning, and interpretation of model results in ways that are accessible and relevant to local stakeholders (Bontkes and Wopereis, 2003; Lipper et al., 2014). In the process of transferring knowledge from researcher to policymaker, stakeholders, such as farmers or extension workers, are commonly only consulted for primary data collection (Becu et al., 2008). This is likely one reason, among many, that even well-developed, scientifically valid decision-support systems that are designed for farmers face a widely-acknowledged "problem of implementation"—low rates of usage by farmers and resource managers, and little contribution to agricultural practice (McCown, 2002; Parker et al., 1997; Rose et al., 2016; Rossi et al., 2014).

Previous efforts to overcome these challenges by incorporating rural stakeholders directly in the modeling process in the Global South are few, but findings suggest various benefits to both researchers and communities. Becu et al. (2008) used a companion modeling process to facilitate communication and collaboration between villages in conflict over water management in northern Thailand, leading to communities' increased dialogue toward definition of collective rules for water sharing. Paudyal et al. (2015) mapped ecosystem services provided by community-managed forests in Nepal, and used participatory geographic information systems and mapping exercises to contextualize and integrate complex spatial information into a simplified visualization process that aided communities in engaging with their local land managers. Barreteau et al. (2000) and D'Aquino et al. (2003) used multi-agent simulation models for negotiation support around the implementation of collective irrigation systems and pastoralist-farmer interactions among communities in Senegal. In each of these cases, local and indigenous knowledge and community participation enriched the modeling *process,* if not the *product*, by using models as heuristic tools for communities to examine their own issues in new ways.

However, the specific outcomes of community-based modeling processes are contingent upon a number of factors that the researcher may not be able to control or even anticipate. Depending on the location and community, these could include the need to bridge large gaps in local understanding of models as representations of reality and not as reality itself; the legacy of others' previous research or international aid activities that influence local expectations of the project; and existing social tensions and power differentials that limit the ability of the researcher to facilitate an equitable community-based process (Becu et al., 2008). The first of these factors is arguably the most controllable by the researcher, and many participatory modeling efforts in rural, resource-poor settings make use of role-playing games and other simplification approaches to build local stakeholders' understanding and ownership of the modeling process. On the assumption that participants will not be able to understand basic concepts of a computerized simulation model, such activities mediate between the model and the community members by presenting a heavily interpreted representation of the model (Becu et al., 2008). A drawback of this approach is that a much greater commitment of time and resources, in the form of increasingly detailed iterations of community feedback and model revision, is required in order to build a well-functioning model that is fully understood by the community, with persistent uncertainty about whether the model's outputs will be viewed as practically relevant at the end of the process.

In this project I explored the initial conditions and considerations at play in applying a crop production model, the Agricultural Policy/Environmental eXtender (APEX), in smallholder agricultural systems in eastern Uganda. These conditions and considerations encompass two areas: the technical setup and configuration of the model and initial correspondence with rural Ugandan farmers about observations, issues, and concerns that may be addressed by such a model. These activities form the early scoping stages of applying APEX and other models at a small scale in Eastern Uganda, using community collaboration approaches guided by participatory research principles.

Context, partnerships, and roles

Supported by a Research and Innovation Fellowship for Agriculture (RIFA) award, I joined the USAID Feed the Future Horticulture Innovation Lab-funded Horticulture Irrigation Project (HIP) and their Ugandan partner organizations for a 5.5-month residency in Uganda's Eastern Region in 2017. The mission of HIP is to engage in "participatory research and development with smallholder farmers to improve irrigation systems in Uganda that fit the local context and address gender issues." At the start of my involvement, HIP was in its third year of operation with six active field sites dispersed across Uganda's Eastern Region. A primary local partner, Teso Women Development Initiatives Uganda (TEWDI), worked closely with the HIP program manager, Abraham Salomon, in carrying out frequent visits to each field site for data collection, maintenance of experimental irrigated and non-irrigated plots, setup and maintenance of irrigation equipment, and meetings with the local committees of farmers involved in the project. Individuals from TEWDI, including Betty Ikalany (TEWDI director) and Helen Acuku (TEWDI projects coordinator), filled critical roles in a number of areas, including by providing local knowledge of farming practices, logistics, transportation, cultural norms, and translation during field site visits.

HIP and the Texas AgriLife Blackland Research and Extension Center (BREC) have an ongoing collaboration with a purpose of adapting and integrating the Agricultural Policy/Environmental eXtender model (APEX), and two other models for regional hydrology and farm-household economics (together known as the Integrated Decision Support System, or IDSS), for the Ugandan smallholder context. BREC and their collaborators had previously adapted the IDSS at a larger scale for agricultural systems in Ghana, Ethiopia, and Tanzania. When fully implemented in Uganda, APEX, and eventually the rest of the IDSS, will contribute a valuable perspective on applying these models in small-scale East African horticultural systems. The collaboration will give HIP and its farmer-collaborators a customized tool for examining the interacting effects of agricultural management practices, climate and weather, regional hydrology, and local-to-regional markets on the productivity of farms.

The six communities actively engaged with HIP represent a range of social and agro-ecological situations (see Appendix 1 - map and overview of characteristics). In its earliest stages, HIP facilitated the formation of an elected irrigation committee at each site comprising individuals with three traits: in good standing in the community, with sufficient time to allocate to project activities, and having or able to obtain the right to use water and land at the target irrigation site. The original project agreements with communities asserted that at least 50% of the irrigation committee members should be women. The committees are responsible for regularly meeting with the research team, consulting with farmers on irrigation technology design, management, and criteria for success, and sharing community's feedback on design and management with the research team. One member of the irrigation committee serves as a compensated site coordinator, who must have a cell phone with regular service and who assists with communication and coordination between the research team and the community.

By the time of my involvement with HIP, three years into the project, most irrigation committees also had roles of elected chairperson, secretary, and mobilizer. While all site coordinators had close familiarity with their community's members, not all were residents of the villages. In some sites, particularly active farmers or community leaders had taken on some of the responsibilities of the site coordinators in serving as first points of contact for the HIP research team. Membership of irrigation committees and farmers actively engaged with the project appeared to be fluid, as individuals' attendance at gatherings, workshops, and trainings seemed to vary. However, at the time of my presence in Uganda, most sites had a core group of approximately four to ten individuals who regularly participated in project activities.

Approach and methods

For the first objective of this project, I examined the process of setting up and using APEX in the eastern Ugandan context, where data for both current and historical weather, climate, soil characteristics, and other important model inputs can be scarce or of poor quality. In these conditions, can the model produce reasonable and relevant outputs that appear to be consistent with reality? Identifying farmers' current concerns and issues, my second objective, is important for anticipating and preparing for future collaborations to design hypothetical scenarios to be examined with APEX or other models and for understanding which aspects of farm systems are most important to represent accurately in a model. Are farmers concerned with the kinds of topics and challenges that a model, whether APEX or another, could address?

APEX model setup and configuration

APEX model description

APEX is a continuous, biophysical simulation model used to evaluate crop management technologies and tradeoffs among agricultural production and environmental effects (Clarke et al., 2017). The model takes inputs of historical weather, soil characteristics, local topographic and hydrologic characteristics, and farmers' management operations, and estimates the impacts of land and farm management and climate on crop productivity, water balance, soil erosion, soil carbon sequestration, pesticide fate and movement, and nutrient cycling and losses (Wang et al., 2012). Appendix 2 provides an overview of the required input data for this project, and how it is formatted for use in APEX.

By allowing the user to define distinct "subareas" that are hydrologically connected, APEX can simulate water and water-borne pollutant movement through complex landscapes, whole farms, and watersheds (Wang et al., 2012). This capability is ideal for modeling water-related outcomes in a setting like rural Uganda, where land use is often highly heterogeneous, even across small areas, and water resources are often communally used and managed. APEX can be soft-linked with the Soil and Water

Assessment Tool (SWAT) and Farming Simulator (FARMSIM) models to conduct integrated, multi-scale and multi-aspect assessment of cropping systems, environmental risk, and nutritional and economic outcomes of new interventions or changes in climate. APEX is an open source application written in Fortran, and maintained by a development and support team at BREC. In this project I utilized existing Windows-based interfaces to set up and learn the functioning of the model. BREC sponsored my attendance at a week-long training for APEX, SWAT, and FARMSIM users in Kumasi, Ghana, which I attended approximately two weeks after arriving in Uganda.

Anticipated challenges in model implementation

I anticipated several specific challenges in applying APEX at a small scale in Ugandan agricultural systems. While the model is rich with capabilities for describing mechanized, small- to large-scale farming systems, some gaps exist in its built-in functionality to describe aspects, especially field tasks carried out through manual labor, typical of Ugandan smallholder agriculture. These gaps may be filled by creating new functions in the model—for example, defining hand-hoeing as a tillage operation in the model where none existed before. However, modifying or creating new farm operations in APEX does not bypass the inherent variability in, for instance, how different farmers perform manual tasks. An aging farmer might drive a hand-hoe into the soil at a different depth than would a young, physically fit farmer. With this tillage depth as one of just a few parameters distinguishing different treatments of tillage in APEX, I expected that the model would fall short in capturing these micro-scale differences in farm operations that might affect the model's outputs.

Although APEX has been applied and validated in developing-country settings, it is not often used to simulate single fields or farms (Clarke et al., 2017; Bizimana et al., 2015, 2014a, 2014b). One reason for this may be that it is difficult to collect sufficient data under controlled conditions for model calibration and validation in this context and at this small scale. Aggregation of observed or simulated weather, interpolated soils data, and typical crop systems and farming practices are more often used in APEX to estimate outcomes for a large area encompassing hundreds or thousands of farm households that are likely to be growing similar crops and using similar management practices (e.g. Clarke et al., 2017). In contrast, this project explored possibilities for applying APEX at the field or farm scale in collaboration with local communities of a few dozen households or less, with limited aggregation of input data in order to maximize the usefulness of model outputs for the community. The difficulty in achieving this downscaling was immediately apparent—this project did not have access to the suite of sophisticated sensors and instrumentation that might be found in a more developed setting; in this context which does not allow for detailed measurements of many aspects of farms and farmers, some aggregation of farmers' practices, soil characteristics, and weather was necessary.

Model data sources and configuration

The APEX model takes inputs as tab-delimited flat files with specific formatting that are stored in a single working directory folder. Input file names are gathered into several “list” flat files, and a single “control” flat file contains the user’s instructions defining which input file names to import for a specific run of the model. The model executable reads the “control,” opens the “list” to verify that the specified input files are available, and then imports the specified input files into the model. Model outputs are produced as new flat files in the working directory. Input files can be broadly categorized as location, weather and climate, soils, farmers’ management practices, hydrology, and model simulation and control. Data sources and setup for each category of model input are discussed here.

Location database

The first step in applying APEX in a new setting is the creation of a database containing general information about the location and its physical characteristics. I created a new APEX location database using geographic, topographic, and climate and weather information specific to eastern Uganda. For this initial implementation of APEX I selected the village of Lwasso from among the sites I could access via HIP. This site is distinct in its position in an elevated valley in the foothills of Mt. Elgon, with cool, wet conditions relative to the nearby plains. For the purpose of setting up APEX and exploring its capabilities, Lwasso was ideal among the six HIP sites because the project team held a longer historical data set on farmers’ activities and practices for the prior seasons.

Weather and climate

Weather and rainfall gauging stations are distributed sparsely in eastern Uganda. I obtained daily historical climate data for the period 1979-2014 for the region near Lwasso from the Climate Forecast System Reanalysis (CFSR) (NCEP, 2017). Previous studies elsewhere in Africa comparing CFSR to observed precipitation data have shown that CFSR data adequately captures the patterns of precipitation, but may over- and under-estimate rainfall amounts especially in mountainous terrain (Berhanu et al., 2016; Wang et al., 2011; Worqlul et al., 2014). I had access to 18 months of historical observed rainfall data for a station approximately 8 kilometers away, but because of this distance, and that the 18 months did not overlap with any period of the data obtainable from CFSR, I chose not to carry out a statistical comparison or bias correction of the CFSR data. Eight days of data were missing from the CFSR set, which I replaced with a numeric string to trigger the model to populate weather data for those days using an internal weather data generator developed by BREC for this gap-filling purpose.

Soil chemical and physical properties

Soil chemical properties were measured by HIP for Lwasso from 20-cm depth composite samples from several plots. Properties measured include pH, organic carbon, total nitrogen, total phosphorus, total sulfur, potassium (exch.), calcium (exch.), magnesium (exch.), zinc (exch.), cation exchange capacity, and totals of aluminum, potassium, silicon, and iron. Physical properties, including sand and clay content, moist bulk density, and texture, were also measured and recorded by HIP for Lwasso.

Farmers’ management practices and operations

Management and operations data collected through farmer surveys at Lwasso in 2016 and 2017 were used as direct input for APEX. Management and operations data include dated records of all activities carried out in the field or plot, for example, planting, weeding, tillage, fertilizer application, pesticide application, irrigation, and accounting of all material inputs and labor. These data were organized into an operations schedule, which is a specifically-formatted timeline of all field operations, with each operation (for example, plowing) selected from a list of nearly 700 operations built into APEX. Each operation in the list contains values for relevant variables (for example, depth of plow penetration and resulting surface roughness). A HIP site coordinator fluent in the local language conducted surveys with participating farmers at approximately biweekly intervals to collect these data, asking farmers to recall their activities for the previous period.

Hydrology

APEX contains sophisticated modules for simulating hydrologic dynamics. I found evidence of existing data from a network of surface water gauging stations in Uganda (Owor et al., 2018). However, the data is not publicly available and my attempts to reach the relevant authorities at the Uganda Ministry of Water and Environment failed. For this reason, and because Lwasso is located at least 5 kilometers from the nearest rivers likely to be gauged, I specified the minimum hydrologic details required in APEX from the available information.

Simulation setup

Among all model outputs, predictions of crop yields are most easily compared to my observations and HIP’s data for Lwasso. I set up APEX for simulations of a four-month cabbage-tomato rotation on a 1-hectare plot using manual irrigation (which I specified as a new APEX operation) and manual tillage. I set the simulations of crop yield outcomes for time periods completely covered by the available CFSR-derived weather data, with the purpose of examining whether, under known weather and soils conditions, the model’s outputs for crop yield would fall within reasonable ranges.

Identifying farmers’ concerns and issues

Informal conversations

I chose to initially communicate with farmers at the HIP sites in an unstructured manner, in order to establish my own broad understanding of communities’ structures and individuals’ roles, unique situations with regard to NGO and development activities in their areas, previous interactions with HIP, and intra-community dynamics that might inform my approach to ongoing engagement about a modeling project. Out of these observations, I formed two general priorities: develop a sense of how to communicate with farmers about modeling tools, and simultaneously develop a sense of farmers’ interests, priorities, and concerns that might be used to build scenarios for analysis in APEX. While scenario development and analysis for various purposes with rural communities is not a new frontier in development research and practice, I determined that scenario development in the present collaborative context, and for model-based analyses, justified an unstructured approach and delayed application of more formalized processes in favor of gaining familiarity with the involved communities and individuals.

Over the course of 5.5 months in Uganda, I made approximately 25 visits to the six HIP field sites. I primarily traveled with TEWDI and HIP project team members, and we frequently chose to bundle several activities into each visit to minimize the burden of our visits on the communities. Knowing that farmers typically used the cool, early-morning hours to complete demanding manual tasks in their plots, we timed visits in order to arrive around midday.

During initial visits I participated in several of HIP's community meetings, field work sessions for setup and maintenance of study plots, and workshops. I pursued informal conversations with farmers in attendance regarding their villages and farms, their perspectives on the use of irrigation, and other general topics around their plots and operations. I also conducted one focus group discussion at Kabos with eight women and men, introducing generally the idea of using computer tools to enhance farm decision-making and inviting attendees to discuss how they have observed and been affected by changes in their farms, community, and environment.

Semi-structured interview protocol

These conversations informed my development of a semi-structured interview protocol to guide further conversations (Appendix 3). With a goal of maximizing the potential for collaboration with the communities, but constrained by the capabilities of the model, I broadly defined several topics and encouraged farmers to freely discuss their related observations, issues, or concerns. The protocol queries individuals' perceptions of recent and potential future change in (1) their benefits from farming, (2) their farm/household resources and assets, (3) the environment surrounding the farm and village area, (4) the people in the community, and (5) their own agricultural management practices. I pre-tested the protocol with farmers at Atari and at Awoja, a village not formally associated with HIP where my TEWDI colleagues had personal contacts, to identify necessary changes in phrasing, introductory explanations, and other aspects of the interview process that could be improved.

Farmer interviews

Subsequently I conducted semi-structured interviews with women and men farmers at Kabos and Lwasso. Each interview lasted approximately one hour, and was conducted in either the individual's home or fields. TEWDI and HIP partners assisted with inviting individuals to speak with me and with translation of our conversation. I recorded written field notes within the expanded margins of the printed interview protocol, and expanded and edited the notes for completion and clarity soon after each interview.

Outcomes

APEX model setup and initial outputs

In considering my aim of understanding whether APEX can produce reasonable and relevant estimations of farm outcomes, at this stage it is clear that further work will be required to adapt this model to Ugandan smallholder agricultural systems. Although I had some intermittent access to the staff at BREC who are currently involved in maintaining and updating the APEX model, I encountered several challenges in setting up and using APEX. Here I briefly review the model's outputs and discuss specific issues I encountered.

Model outputs

For a manually maintained cabbage-tomato rotation, model output for annual yield of cabbage was 0.01 ton/ha and yield of tomato was 0.00 ton/ha. These values did not change when I specified different lengths of simulation periods (between one and three years), nor when I moved the start of the simulation to different years within the known weather period (1990, 2000, 2010). One output variable that changed noticeably was excess water stress on the crop, which spiked in years of heavier rainfall and dropped near zero in dry years.

These initial outputs suggest the model is vastly under-estimating yields, likely due to issues with the configuration, the data, or both. While yields of most crop systems I observed in Uganda, including at Lwasso, are very low compared to similar systems in the developed world, harvest data collected by HIP in 2016 show at least several intermittent harvests of 10-30 kg (0.01-0.03 ton) each throughout a year from plots smaller than one hectare.

Output issues and discussion

Model configuration issues might include that most crop management operations used to build the operations schedule in APEX are not specified for manual crop maintenance. For example, although I developed a new manual-irrigation operation based on APEX's existing irrigation operations, the manual operation caused the model to crash when used during a run. In its place I was forced to select the existing mechanized irrigation operation that appeared closest to a manual application (sprinkler irrigation with the fewest nonzero mechanical and equipment variables specified). I made similar compromises in identifying other operations. Additionally, my setup of the management operations schedule in APEX caused the application to crash due to an internal error (memory access violation) when certain operations were repeated in the schedule more than 20 times—for instance, daily or bi-daily applications of small amounts of irrigation over the course of the two 4-month seasons. I am currently working with the developers at BREC to resolve this issue.

A comparison of my operation schedule with templates built into APEX hint at the specific challenge mentioned by Lipper et al. (2014) of downscaling models for local relevance. Farmers in Uganda typically operate in two distinct seasons in accordance with temporal rainfall patterns, with each of two growing seasons lasting 4-5 months alternating with fallow dry periods. Within a season, a farmer is often quite active in the field on a day-to-day basis with plowing, irrigation, fertilizing, and weeding consuming a large number of hours. Decisions affecting yield outcomes are made on a temporal scale of days, over spatial scales of a hectare or less. By contrast, APEX operations schedule templates, publications, and previous cases of applications show management schedules of a few operations spread over several months. Without a deeper knowledge of the internals of the model, it is uncertain whether aggregating some of my farmer-reported data, for example successive daily irrigation applications into one larger weekly application, would affect the quality of the model's outputs or its ability to run without errors.

Farmer interviews

Interviews and informal conversations with farmers served my aim of understanding whether farmers are concerned with the kinds of topics and challenges that APEX could address, and also revealed several important considerations for carrying out a more formalized scenario design and analysis process in collaboration with communities. Here I discuss three valuable outcomes of these conversations. First, our interviews covered a number of practical issues and concerns for farmers, some of which may be addressed with APEX and some of which would require other tools or approaches. Second, I observed a potential preference by farmers for discussing certain topics that they may associate with the interests and activities of HIP, which are oriented more toward horticulture and irrigation than are my own individual research interests. Third, some farmers expressed a strong desire for reciprocity in the form of feedback or informational products from my research efforts, hinting at a precedent for outsider research teams to take up farmers' time in surveys and interviews without returning results or outputs of the investigation to the communities.

Practical issues and concerns expressed by farmers

Practical farming issues that farmers discussed in interviews are represented in a causal map (Appendix 4). Farmers readily made connections among issues of climate and weather, agricultural practices, crop yields, environmental changes, local and regional market dynamics, local labor force, and status of health issues in their communities. Many individuals I spoke with described with detail the ways in which they have been affected by decreases in rain in the past 3-5 years. With uncertainty about the timing and amount of precipitation, farmers selected crops such as cassava that can more likely withstand dry periods, replacing vegetables that are more nutritious in both their fields and their own diets. One woman at Kyekidde described her current habit of watching the horizon for rain clouds, so that she might immediately pick up the seeds she had measured and stored at home and rush to her garden to plant them ahead of a rainfall that could enable their quick germination. A woman farmer at Kabos discussed how the unpredictable rains have affected labor availability: many farmers have abandoned their fields altogether for employment as motorbike or taxi drivers or in retail positions in town. Whereas farmers used to help one another with labor-intensive tasks, such as tillage, nowadays individuals who have persisted in farming are less likely to trade such favors because each needs to attend to their own fields when a possibly-fleeting rainfall is eminent. Not all farmers seemed to worry over water: in Lwasso, several farmers I spoke with were conscious of the threat of drought affecting their crop production, but they placed greater emphasis on the difficulty of affording agricultural inputs like fertilizer and pesticides. Individuals in Kabos worried that a pest or disease outbreak, similar to one affecting cassava several years prior, would wipe out one or more of their staple crops—especially crops that are otherwise hardy to the variability in weather patterns that farmers observed as being increasingly common.

The complexity of factors affecting these communities' agricultural outcomes, both endogenous and exogenous, is evident in the range of issues they discussed. This bolsters the case for the application of a model-based decision support tool that could contribute toward simplifying the number of choices that farmers must make. However, one of the concerns mentioned in nearly every conversation I had is not readily estimated by APEX or by its associated models in the IDSS: that of an imminent pest or disease outbreak that could destroy entire seasons' crops and destabilize local markets. Although APEX has a function for incorporating the portion of in-field losses due to pests into calculations of yields, pest and disease occurrence is influenced by ecological factors far outside the farm, landscape, or even regional system, and cannot be predicted with tools in the IDSS. The inability of APEX to estimate outcomes for some issues, such as this, that loom large for farmers suggests that a model-based approach should be undertaken in parallel with other established mechanisms for agricultural advising and extension that can address issues such as pest and disease prevention.

Researcher association with Horticulture Irrigation Project

Although I was a member of the HIP team and participated in a number of HIP's community-based activities while in Uganda, my individual research interests objectives were more broadly concerned with understanding the issues farmers experience and their understandings of the origins and results of those issues—including horticulture and irrigation, but extending to cultivation of non-horticulture crops and beyond the field to household-level and community-level economic outcomes. However, several farmers stayed close to the topics of rainfall and irrigation throughout our conversations, and I was not able to determine whether these were really their only concerns, or if they assumed these were they issues I wanted to know most about as a member of the HIP team.

Reciprocity in the research process

Particularly in Lwasso, where research and development activities by other groups seem to have taken place in the relatively recent past, farmers were also concerned about the issue of my own research plan and the potential that I would consume the time and energy of individuals in the community and not return with the results of the project. Since I was carrying out the initial, information-gathering stages of a project, I was not able to demonstrate to farmers a commitment to the dissemination of my project results within the foreseeable future.

Building a participatory modeling approach

Using lessons learned from the above-described engagement with communities of farmers in eastern Uganda, and initial setup of APEX for small-scale model implementation, I developed a proposal oriented toward continuing collaboration with these communities during my PhD program. The proposal addresses the main components of defining and implementing a model-based research project with a rural Ugandan community, drawing on principles of participatory research to inform each stage of the research process.

Principles of participatory research

Participatory research uses methods that maximize community involvement and agency in each stage of the research process. Nine principles of community-based participatory research are broadly defined for application in public health, a field in which participatory methods have been actively applied and evaluated. While others identify additions or modifications to these principles, most converge around a "commitment to conducting research that shares power with and engages community partners in the research process and that benefits the communities involved" (Israel et al., 2005). The principles include:

1) Acknowledging community as a unit of identity
2) Building on strengths and resources within a community
3) Facilitating collaborative partnerships in all phases of research, using an empowering and power-sharing process that attends to social inequalities
4) Fostering co-learning and capacity-building among all partners
5) Integrating and achieving a balance between knowledge generation and intervention for the mutual benefit of all partners
6) Focusing on the local relevance of the issue under study and on ecological perspectives that recognize multiple determinants of the issue
7) Using a cyclical and iterative process that draws on the competencies of each partner
8) Disseminating results to all partners, and involving them in wider dissemination of results
9) Involving a long-term process and commitment to sustainability

These principles form a set of ideals, but there is no single approach to implementing a participatory process, and in practice some of these principles may be impractical, or may even create a burden on a participating community. The application of methods guided by these principles must be carefully considered by the partners in the project and specifically informed by the context.

Proposal for community-based participatory application of model

Defining the Community, Community Partners, and the Issue

An early step in any community-collaborative research approach is the definition of a community with which to partner. In this project several considerations will influence this process, including the practical accessibility of rural areas, my prior contacts with six Ugandan villages via HIP, the scope of issues that can be represented with some accuracy in a computer-based model, the degree to which these issues are of interest to potential community partners, and existing shared identities among farmers and within communities.

In this project I will continue my existing relationships, established via my involvement with HIP, with six villages in eastern Uganda. I will approach one to two HIP innovation sites via contact with their site coordinators. With their assistance I will introduce the broad concepts of a computer-based modeling tool, the kinds of topics and questions a model is capable of addressing, and how it might be useful and relevant, and invite them to discuss initial interests and concerns about participation in a project. Subsequently I will request that they choose whether to invite my project collaborators and me for further discussion and ultimate agreement of whether to form a partnership. This ultimate agreement will be based in part on the community's assessment of whether the scope of issues that can be addressed in the model are of relevance or interest to them. Ideally, two communities will be identified that occupy distinct agro-ecological settings, generating additional value for the researcher in enabling a comparison of the process across biophysical and social conditions.

Although the model, which is tailored to biophysical and/or economic farm system dynamics, limits the set of issues that can be collaboratively examined, as a researcher my interest at this stage is in the *deployment and utility of a tool* rather than in the empirical study of a specific aspect of rural life in Uganda. Because of this distinction, I will be able to accommodate a wide set of farmer-defined issues. I expect that the group I engage with will be self-selected by members' interests in certain issues, and issues will be narrowed by members, in an iterative process. I also anticipate that identities or characteristics already shared within the community—e.g. affiliation with a village and/or tribe, and occupation in agriculture—will inform the membership of the group.

Defining Roles and Responsibilities

Stoecker (2008) grounds a discussion of the roles of academics in participatory research in several basic questions, starting with: What is this participatory project trying to do? This question is important to articulating the social infrastructure of my project that will be needed in order to generate mutual benefits for my work and for the community. The project's research objective of identifying a process for community-researcher collaboration in modeling is linked with a goal of improving livelihoods for smallholder farmers in resource-scarce environments. Especially in a non-Western cultural context that gives relatively less weight to "empiricoanalytic reason", site-based coordinators and other "locals" with exposure to researchers from outside the community will be critical to creating a continuous channel of communication among all members of the project (Wallerstein and Duran, 2008).

In recognition that genuine, sustainable social change is likely more effective in improving livelihoods than a research-based model development objective, I disaggregate the relatively nuts-and-bolts process of *making the model work with farmer input* from the processes of *building capacity through collective engagement with a project*. This distinction provides a basis for defining the major roles in this project. I will continue to work with staff from TEWDI Uganda and with HIP's local site coordinators, who will likely fill roles of "community organizer", "popular educator", and "preceptor", with a focus in facilitating engagement with the community and mediating along cultural and language dimensions of the collaboration (Stoecker, 2008; Wallerstein et al., 2005). Depending upon the community's response to the topical constraints posed by the model, my own responsibility may shift from "initiator" to "consultant": once the project has been initiated and the constraints of the model established, much of the control over which issues to examine with the model will be given to community participants. If completed, this shift would bring my project a step closer to the ideal put forward by Stoecker (2008), of the academic as consultantcollaborator; however, the community's desire and capacity to accept that control, which is not assumed, will also influence how roles and working relationships are defined.

Structuring the Collaboration

Although my project will make use of HIP's existing relationships and lessons learned, it will not necessarily duplicate HIP's collaboration structure. With a goal of making the "partnership reflect the culture of the community and not simply replicate a *professional culture*," consultation with TEWDI staff and community members will be used to identify components of the HIP collaboration that were mutually effective, and those that should be changed in order to maximize the community's participation and agency (Wallerstein et al., 2005).

A few structural aspects of HIP emerge at this stage that seem to have been effective, and if agreed among all partners these may be codified with participants in my project. Rural communities who interact regularly with development NGOs in Uganda, including with HIP, seem to often adopt their own internal organizing structures, including the identification of a committee consisting of a chairperson, secretary, mobilizer, and a group of member participants. A site coordinator, often an agricultural extension agent with social ties to the community, will be involved as a main point of contact for the committee and as a liaison with TEWDI. I will work with TEWDI and HIP staff in synthesizing my own research objectives with the community's objectives. Norms for the interactions of each of these components with one another, and with the whole, will be openly established at the outset of the project with the assistance of such methods as the "norming exercise", which will ideally create space for the rethinking and modification by community members of their dominant modes of interaction with outside researchers (Becker et al., 2005). In alignment with lessons learned from HIP, Uganda's limited transportation and communication infrastructure will likely make the use of an inclusive advisory or steering committee, so prominent in the participatory methods literature, impractical for this project.

Stages of the research process

Defining the problem

The selection of a topic for examination, based on the community's assessment of its issues and concerns, will be guided by the capabilities of the modeling tools, but might range anywhere from the scarcity of rainfall to the unpredictability of local and regional agricultural markets.

With a known and discrete set of issues addressable in the model, the refinement of a smaller set of problems will be pursued through prioritization using a modified Delphi process (Minkler and Hancock, 2003). A Delphi survey is a method for gathering opinions from a large group, in which participants are asked to prioritize a narrowing set of issues in two stages, after which the aggregated results are shared within the group and participants are given an opportunity to revise their previous prioritizations based on the collective opinion (Minkler and Hancock, 2003). Assisted by

TEWDI staff and site coordinators, I will carry out a three-step survey to identify and rank participants' and the group's top issues of concern in agricultural management.

The resulting set of priority issues will be brought back to the community for discussion and ultimate agreement for advancement into the modeling process. The site coordinator and TEWDI staff will facilitate a focus group with community members and researchers as participants, creating a platform for authentic expression by the community in the presence of the researcher (Kieffer et al., 2005). While a focus group approach to finalizing problem definition may not address the possible lack of representation or silencing of lower-status members of the community, ideally the method will advance a genuine partnership by balancing power between the researcher and the community (Chavez et al., 2008; Wallerstein and Duran, 2008).

Defining the Research Question

In a manner based on Ballard et al. (2008), this project will address one or more flexible research questions determined by the community, which will fit within a broader, controlled question determined by the researcher. Starting from a set of priority issues narrowed by the community, I will work with community participants, TEWDI partners, and site coordinators to define specific scenarios of interest. For example, for hypothetical issues of soil erosion and yield, community questions might include: "How should I distribute water over my field in order to minimize soil erosion?" or "How will switching to using purchased fertilizers, instead of manure, affect the yield of my crop this season, and will this effect persist over other seasons?" The scenario development and analysis process is further discussed in the "analyzing and interpreting model outputs" section below.

As Wilmsen et al. (2008) highlight, "all knowledge systems are capable of providing valuable insight," and farmers' articulations of research questions may include assumed causal relationships that are not supported by current Western scientific knowledge. Recognizing and validating these articulations will be an important aspect of addressing my broad question of interest, "How can models be made useful for farmers?" To maximize the potential benefit and utility of model-based tools for farmers, I will have a critical task of working within local knowledge systems that are conditioned by rural Ugandan communities' variable access to education and resources, and influenced by religious traditions. These factors will challenge the feasibility of fully utilizing a biophysical and economic model, and in this area I will need to be especially agile in integrating local knowledge with the model. Just as scientific information is examined and critiqued in the West before being inaugurated as "knowledge," I will use all available resources, including relationships with TEWDI staff and other local connections, to understand the origins of local explanations and identify when it is relevant, appropriate, and culturally sensitive to offer alternative perspectives that might represent a benefit, rather than an imposition, to the farmer (Wilmsen et al., 2008).

Designing the Research Project

In integrating objectives around both the development of a research product (a configured and functional model) and a process (its uptake and utility for a wide set of potential community concerns), the project design process can respond to the three core criteria defined by Wulfhorst et al. (2008) for participatory research design.

Conditions for *community-centered control* involving ownership, credibility, and continuity of trust will be established by inviting community members to identify the issues that they care about, validating and using their contributions of knowledge in a meaningful way, and building and meeting mutual expectations that are within the capacities of project members. Observations from my experiences working with HIP suggest that the stark differentials in background, culture, and access to resources between researcher and community may make genuine community control difficult to achieve, and this will be navigated by emphasizing the roles of the site coordinator and TEWDI as integrators of community and researcher perspectives via intentional group process and collaboration strategies.

Reciprocal production of knowledge will be fostered through iterations of input and reflection, using such strategies as community dialogues for validations of the accuracy of the model's initial outputs (Minkler and Hancock, 2003). Without a regular practice of consolidating observations of the functioning of their farms, some HIP community members reported that the process of examining and explaining the status of their plots and fields to HIP researchers was in itself a helpful exercise for learning to track changes in productivity relative to changes in their management practices. In this vein, my project will ideally build farmer capacities to monitor and adaptively manage their fields for resilience to both agronomic and economic disturbances. Finally, *outcomes and distribution of benefits* will be discussed openly at the outset, and revisited throughout, with the purpose of establishing a formalized agreement on the mutual responsibilities and expectations for contribution and benefit from project activities.

Data collection

Data required in this project will include, at minimum, quantitative measures of general agronomic, environmental, and topographic features of the community's local area. Dependent on the issues selected by the community for further modeling, additional data might include farmers' descriptions of activities such as tillage or planting, irrigation, yields, observations of soil losses, changes in water sources, or economic characteristics of households and local markets.

A variety of data collection tools may be used to meet these needs, tailored to the capacities of the individuals tasked with collecting it. While the project team will maintain the option for community members to participate in gathering and collating such data, based on my observations I expect that "recognizing when participation is needed and from whom" will best allow the project to balance participation and members' competing livelihood demands (Schulz et al., 2005). Although it relaxes the participatory ideal of building data collection competencies within the community, this approach will also allow the project to more efficiently gather information necessary to proceed to activities, such as verifying model outputs or analyzing scenarios, that may be more interesting and beneficial for community members (Eng et al., 2005).

The question of which community members' perspectives and information are represented in the data is also important. Unless I directly select participants, individuals' status in the community along age, economic, and gender dimensions will likely determine whose priorities and concerns are included. However, while perhaps idealized in theory, resisting local mechanisms of social oppression on a point of principle might also erode my ability to connect with some members of the community. Successfully navigating these issues will be the product of trust and mutual commitment over time to authentic understanding, and a balanced accommodation of cultural norms while maximizing the participation of traditionally oppressed groups (Wallerstein and Duran, 2008).

Analyzing and interpreting model outputs

Model outputs will include initial predictions of the outcomes of target parameters based upon data collected far in the past, and for which the actual outcomes are already known. In model validation, various methods are used to demonstrate that the configured model is capable of making accurate simulations (Refsgaard, 1997 cited in Moriasi et al., 2007). Ideally, the performance of the fully configured APEX model (or another model) will be evaluated statistically and by comparison with local knowledge. Multiple statistical criteria can be considered to assess different aspects of model accuracy. Nash-Sutcliffe efficiency, percent bias, and root mean square error are recommended by Moriasi et al. (2007) and Wang et al. (2012) for quantification of accuracy in APEX and other integrated hydrologic models. However, availability and quality of observed data for model validation features highly in determining which criteria to use. Comparisons of predicted and observed data over time can be used to identify seasonal or other time-related discrepancies between observed and simulated data.

Most applications of APEX and other models involve using these statistical methods to examine the model's performance in comparison with observed data. However, in the present context a statistical validation process may be unreliable because of limited observed data at the household or farm scale. In place of a validation process, at the suggestion of my collaborators at BREC, I propose to instead *verify* the model's outputs and performance using the community's local knowledge, input from TEWDI staff with knowledge in local agriculture, and other local expert sources.

Model verification offers an opportunity for the kind of reciprocity highlighted by Wilmsen et al. (2008) as crucial for addressing the power effects of the Western model of knowing. As previously discussed, farmer interpretations and analysis of past environmental or agricultural events will be conditioned by "hybrid knowledge produced by the unfolding of uneven relationships of power in research and development processes" (Wulfhorst et al., 2008). I will conduct a non-technical model verification process via focus groups to present the model's predictions and structure the community's critical evaluation of results. In addition to examining outputs, this exercise will ideally reveal the assumptions of fundamental agronomic processes inherent in the model, and allow for comparison with local understandings of crop production that will enrich subsequent uses of the model.

A major challenge to verifying the model outputs will be the communication, or "translation," of model parameters and their predicted values to the community.

Toward structuring this “translation” between the model and the farmers, I developed an initial framework for interpretation and analysis of influential model parameters with community members (Appendix 5). Each parameter is linked to an agronomic process that is known to influence crop yields and environmental outcomes (columns 1 and 2), and each of these is interpreted in a non-technical way that emphasizes observable symptoms or changes in a field or plot (column 3). I will ask farmers to discuss the range of values or conditions they would typically expect for each parameter (column 4). These ranges can then be re-interpreted back into model parameter ranges, within which a well-functioning model's estimates should fall. I will make adjustments within the model until estimates agree with any available observed data and with farmers' observations.

The verified model can then be used to examine scenarios and questions of interest to the community. In an extension of the initial conversations I conducted with farmers in 2017, I will use the input and output parameters and predictive capabilities of the model as a guide for discussing current conditions and future scenarios for examination. I will use small group discussion sessions and similar approaches to craft model scenarios and questions, with different sessions for men and women farmers if possible to create the potential for examining how scenarios of interest might vary by gender.

Other than establishing the broad set of topics the model can feasibly address, I will not impose constraints on the kinds of questions farmers define. However, I anticipate two types of inquiries to emerge from this process:

- Scenarios: What will be the effects of a change in [this part of my system]? In the model, this is represented by the influence of one or few parameters on many. Examples:
  - What would happen if I changed planting rotations of my crops?
  - What would happen if we expand our use of irrigation, and an extreme drought occurs?
- Questions: What do we need to change to optimize [this part of my system]? In the model, this is represented by the influence of many parameters on one or a few of greatest interest. Examples:
  - What do I need to do to achieve a higher yield?
  - What practices do I need to focus on to prevent long-term degradation of my soil?

I will use a process similar to that described by the UN FAO (2013) to establish the underlying drivers of change that communities expect to play a role in their near and long-term farm production outcomes. This process will include a group exercise in building a historical timeline of general significant events and specific regional agricultural events, with the purpose of sensitizing participants to identifying patterns, trends, deep changes, and stability/instability dynamics in environment and society. The timeline exercise forms a basis for discussions of the current context, issues, and challenges for agriculture in the local-to-regional area. This is followed by a discussion of the driving forces, or factors that shape the future, including distinguishing those that are known (such as population growth or the presence of international development actors) from those that are uncertain (such as the nature and structure of the economy or national-level agricultural policies). These underlying drivers will be used as a "background" against which to examine the scenarios and questions of interest to the participants. For example, an underlying driver that participants might identify could include ongoing variability in the timing of rainy and dry periods throughout the year (see first and third rows in Appendix 5). If all participants agree that this underlying driver will affect their agricultural outcomes, the climate and weather component in the model may be revised and additional parameters – such as different sets of management practices – can be tested in the context of seasonal variation in precipitation and temperatures. Identifying such underlying drivers will allow for the narrowing of the set of conditions under consideration for scenarios, simplifying the discussion process with participants. Underlying drivers – such as changing constraints on access to agricultural inputs -- may also be examined as their own scenarios with the model, leaving other management parameters static. Interpretations of drivers, such as those suggested in Appendix 5, will also be validated in discussion with community members.

An expanded version of Appendix 5, along with detailed notes of the discussion, will be used to record the underlying drivers of change identified by farmers, and to link these to model parameters. Scenarios will thus be recorded both narratively using farmer input, and as sets of changes to model parameters.

Disseminating and sharing results

The distancing geographic and institutional boundaries between the community and myself make a truly participatory dissemination strategy difficult to implement. However, I expect to build farmer control of information and results into each stage of the project by openly discussing the community's needs and preferences from the early stages of the project. Prior to seeing the outputs of the model, it is impossible to know if they present concerns for members of the collaboration in their dissemination to a wider population. The researcher, TEWDI, and site coordinator will organize a discussion with the community committee of the potential sensitivity, proprietary nature, or other concerns about project results.

If considered shareable with a local or regional audience, results of the project will be prepared for dissemination within the community and among neighboring communities. A number of studies of information transfer in regions with low literacy rates find that farmers often learn most from one another, and that social interactions strongly influence the transfer and uptake of new innovations or technologies (Mashavave et al., 2013). It is in this dissemination and sharing stage that this project has the greatest potential in addressing the "problem of implementation" that affects the impact of many decision-support tools (McCown, 2002).

In this case I will work with all collaborators, and especially the community and TEWDI staff, in identifying the methods for dissemination that suit the needs of the community, are feasible with project timelines and budget, and that maintain the relevance and usefulness of project results for farmers. Initial ideas include the creation of a set of decision trees, which have been effectively used in community-based research and development in the Global South for many years (Brown, 2006). Using structured group mapping activities, the scenario-specific model outputs could be graphically diagrammed as “if this, then that” logical frameworks that describe farmers’ practical options for responding to specific issues examined using the models, and expected outcomes predicted by the models for each response strategy. Another method addressing farmers’ social learning capacities could include facilitating a series of gatherings in which community members disseminate project findings to a wider audience of neighbors.

I will also develop and present a set of general findings and lessons from my project to the community for input during individual and group meetings. Community reflections will be incorporated into subsequent syntheses and reports stemming from the project. However, as Stoecker (2008) and others note, academics and especially graduate students engaged in community-based participatory research are likely to be forced to compromise some of its principles in order to conform to expectations from advisors, departments, the university, or potential publishers.

Taking action based on results

In its pursuit of answers to farmer-defined questions, by scoping adaptations to existing farm system management practices, and by building iterations of farmer evaluation and critique of model outputs into the research design, the project will work to maximize its production of relevant and farmer-actionable knowledge.

Results of the project will be considered jointly “owned” by the community and the researcher, and use of the results in subsequent actions will be mutually agreed and revisited during the project cycle. From the two nested research objectives, two scales of action seem likely: the community acting with TEWDI at a local/regional scale to make practical improvements to agricultural systems, and the researcher acting with TEWDI at a national or greater scale to influence agricultural policy regimes, development approaches by NGOs, and other institutional and structural changes. I do not expect rural Ugandan farmers to continue to carry out independent modeling projects, but I do expect that engagement with my project will involve farmers in new approaches to evaluating practical aspects of their own and others’ farm systems that can lead to material and livelihood benefits. Thus, in place of a literal adherence to the final participatory principle of project sustainability, a transparent discussion with participants regarding mutual benefits at the start of the project will include a dialogue around how new information and processes for developing decision-support tools might be optimized during the project to serve the community’s long-term action and social change ideals (Israel et al., 2005).

Conclusions

Outcomes from my initial efforts in setting up the APEX model showed, as I expected, that a Ugandan smallholder agricultural system contains a set of characteristics that make utilizing this model uniquely challenging. These characteristics include the difficulty of obtaining data to support using all the capabilities of the model, and that the model’s internally-defined farm operations do not include some manual operations that are widely used in Ugandan agriculture. Despite these issues, and the difficulty I encountered in working with APEX, I think that further work with the model and collaboration with BREC can result in a model that is functional in estimating outcomes for smallholder farm systems.

Interviews with farmers revealed that many of their concerns and issues seem to align with the capabilities of APEX and other models, such as the relationship between continuous cultivation and soil erosion, and that using a model to derive decision-support tools in this setting. Both of the challenges I observed—bias farmer responses due to my being associated with an irrigation project, and a desire for reciprocity in the research process—can be addressed through the application of participatory principles in further research activities.

The proposed project will continue in configuring the APEX model to examine farm system dynamics and scenarios at the site scale. Future research directions might include setting up the other component models of the Integrated Decision Support System. The Soil and Water Assessment Tool (SWAT) may be used to examine upstream and downstream effects of irrigation and other agricultural management decisions. The farm income and nutrition simulator, FARMSIM, may be used to extend economic analyses from the outcomes from the APEX model. The full application of the IDSS would link agricultural production, economic outcomes, and environmental effects of the introduction of new irrigation technologies in the Ugandan smallholder context, providing information relevant to farmers, NGOs and development organizations, and the government/policy arena. Given the difficulties encountered at this stage in configuring APEX for this purpose, other models may also be considered which may better suit the purpose of collaboration between the researcher and farmer communities.

The ideal identification of two study sites for this proposal is intended to provide a basis for comparison of applications of the models and scenario outcomes between differing agro-ecological and social contexts. This comparison would be enriched by expanding the proposed activities to more of the remaining four sites involved with HIP, which represent further variation in system scale, topography, agricultural management, social dynamics, and resources. In sum, outcomes from these activities could provide a strong basis for identification and selection of models and model-based tools for both researchers and development practitioners working in similar systems in sub-Saharan Africa.

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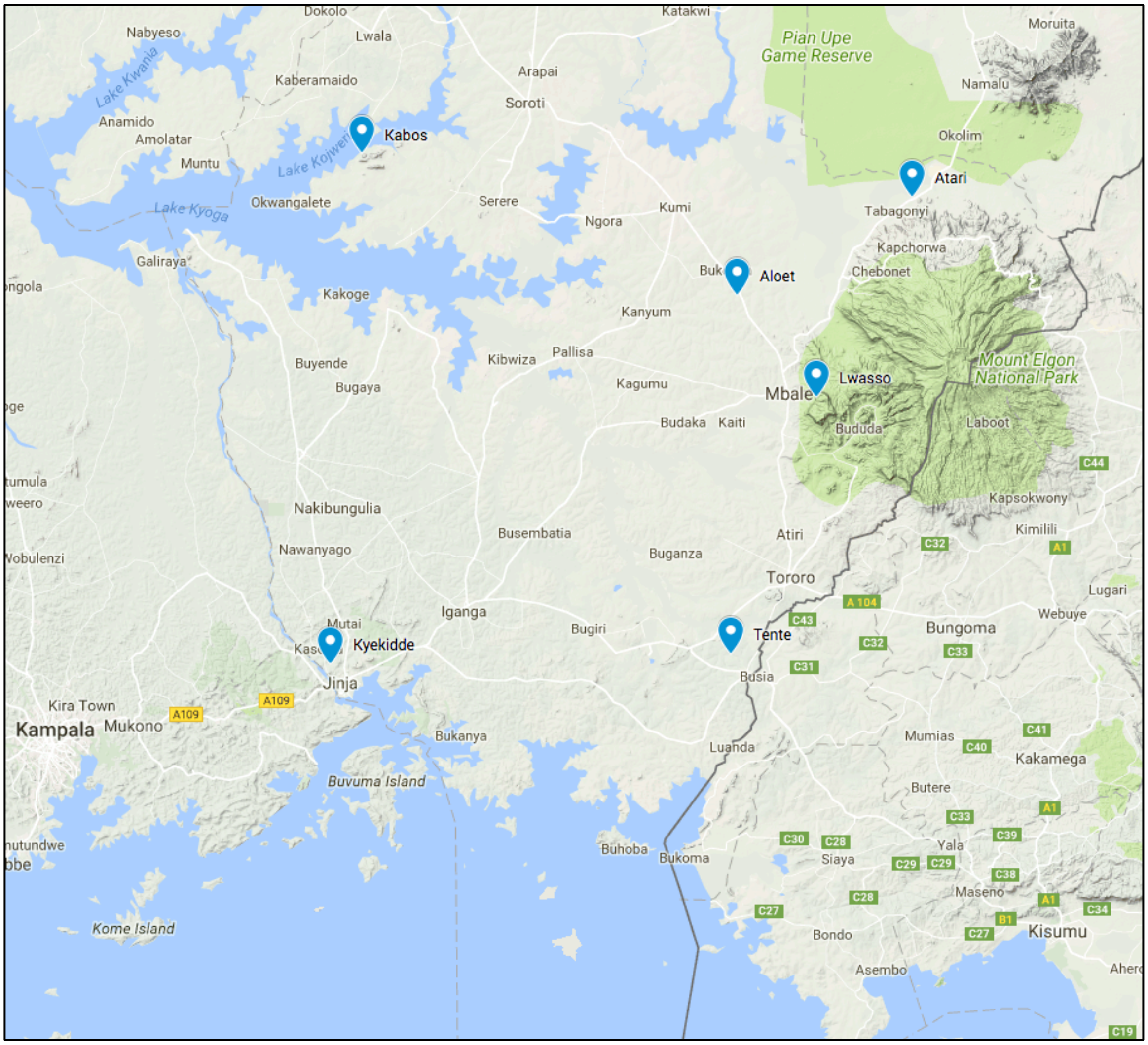
Appendices

Appendix 1

Communities active with the Horticulture Irrigation Project, summary characteristics, and locations (next page).

Site Name	Farmers	Typical holding size (ha)	Landscape features
Lwasso	~ 50	< 0.1 ha	• elevated valley in foothills of Mt. Elgon • surrounded by near-vertical cliff to west and irregular varying slope to east, north, and south • ~1.5% slope
Kabos	20-30	1.25 ha	• gentle slope from mild undulating plain • < 100 meters from shore of Lake Kyoga
Aloet	< 15	< 1 ha	• narrow inland valley surrounded by mild undulating plain • ~1% slope
Kyekidde	~ 50	< 1 ha	• cultivated valley in undulating terrain • surrounded by moderate (2-5%) slopes • near Nile River
Atari	~ 40	0.5 – 1 ha	• flat plain north of Mt. Elgon • near large irrigation scheme constructed at edge of wetland
Tente	~ 50	~ 1 ha	• undulating terrain • near Busia town and Kenya border



Locations of six HIP sites in relation to the capital city Kampala (to the west), Lake Victoria (to the south), and the Kenya border (to the east). Basemap source: Google.

Appendix 2

APEX input data categories, data formatting, and variables

Model input data	Input file
Location characteristics	**Formatted text file containing**: • size of **subarea** under analysis • average, maximum, and minimum slope • longest and shortest slope length

Weather	**Formatted text file containing:**
	• daily historical weather data for the period 1979-2014
	  o Variables: Maximum temperature, minimum temperature, solar radiation, precipitation, relative humidity, wind speed
	• Monthly average values of daily weather variables, and:
	  o Probability of a day with precipitation followed by a day without precipitation
	  o Probability of a day with precipitation followed by another day with precipitation
	  o Monthly average days with rain
	  o Standard deviation of min temp, max temp, and precipitation

Soils	**Formatted text file containing for each soil depth layer:** • Layer thickness • Bulk density • Wilting point • Field capacity • Sand content • Clay content • Silt content • Organic nitrogen • pH • Organic carbon • Cation Exchange Capacity • Saturated Conductivity
Farmers' management practices and operations	**Formatted text file containing an operations schedule with:** • the date of a farmer's action • the type of action (e.g. irrigation, fertilize) • values defining the operation (millimeters of irrigation, rate of fertilizer application)

Appendix 3

Interview Guide
Participatory crop modeling and scenario development

1. Introduction:

In this project, we are able to test out solutions to many challenges farmers in Uganda have in irrigation. However, there are many other challenges that take many years to have an impact on farmers' lives.

In order to identify solutions to some of these long-term challenges, we are using a tool on the computer that allows us to predict what could happen in 10 – 50 years.

We can predict changes based on the data that you have already been providing us regarding the management of your plots, and based on different ways that the environment changes, communities change, and farmers' practices change. We want to use this tool to help identify solutions to questions or concerns that you might have regarding the long-term outcomes of your farming decisions, and might have regarding the effects of factors outside your control like weather or climate.

Based on your responses, we will try to predict what could happen in the long term if different changes happen.

If possible, we will bring the results from the computer tool back to you as information you may choose to use in your farming approaches.

2. Questions:

A. <u>Outcomes:</u>

1. What are the most important benefits you get from farming?
    a. Possible prompt: consider farming as compared to other livelihoods or income sources
2. How have these benefits changed in the past 5 years?
3. How do you think these benefits could change in future years?
   Prompts: Annual income, Income variability, staple foods, nutritional diversity, etc…

4. What are the resources you have on your plots that you put into growing crops?
    a. Possible prompt: consider broad categories of natural, material, cash, and labor resources
5. How have these resources changed in the past 5 years?
    a. Possible prompt: consider supply and affordability
6. How do you think these resources could change in future years?

Prompts: Soil quality, agricultural assets, livestock., water access, etc…

B. Scenarios

7. What changes in the environment have you seen happening in the past 5 years?
8. How have these changes affected farming for you?
9. Do you expect these changes to continue? How will they affect you if they continue?

Prompts: Within season drought, delayed panting dates, excess rains, soil erosion, soil fertility, etc

10. What changes in your community related to farming have you seen happening in the past 5 years?
    a. Possible prompt: composition of labor, age of farmers
11. How have these changes affected farming for you?
12. Do you expect these changes to continue? How will they affect you if they continue?

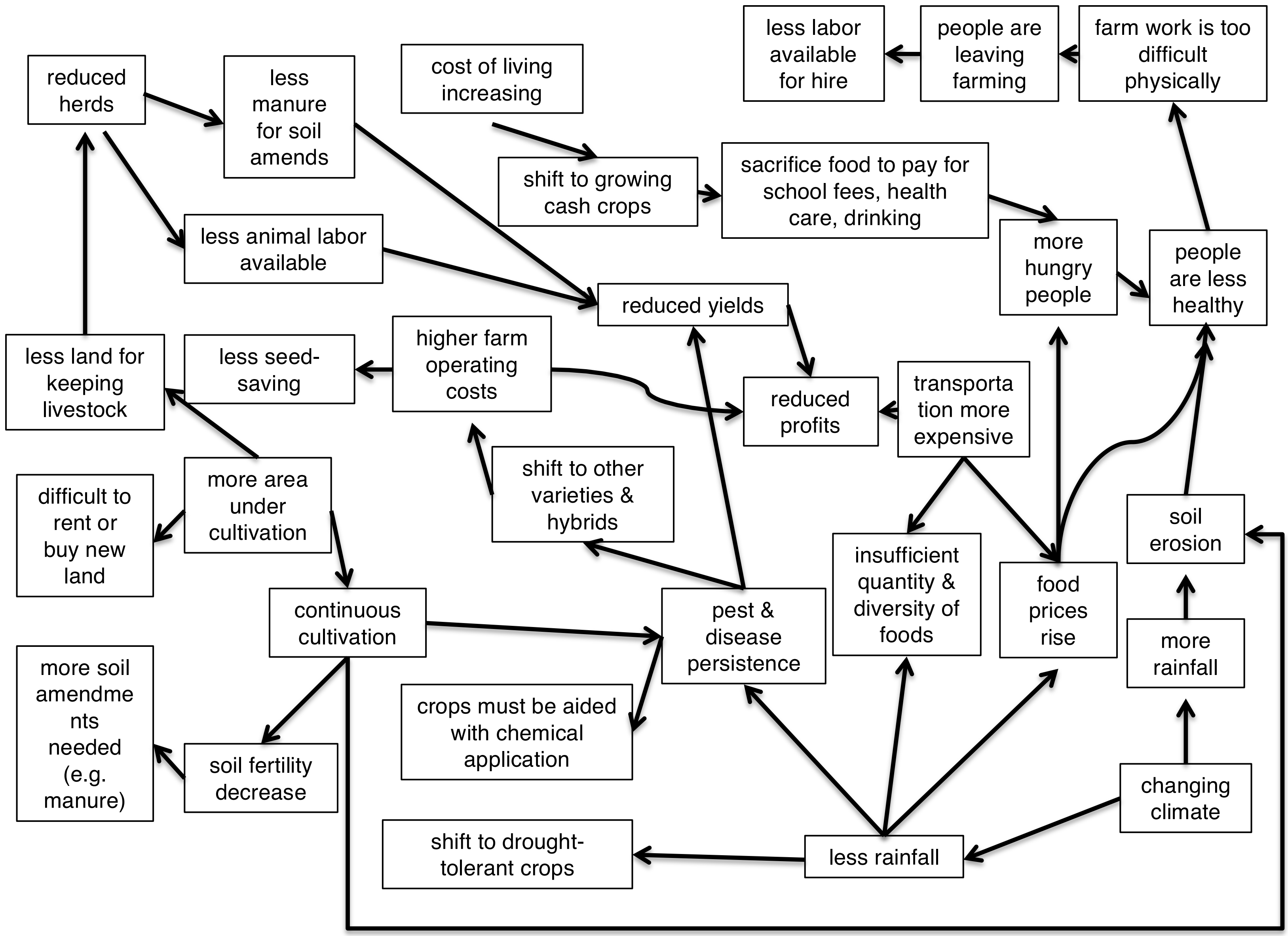
    Prompts: Land use change, off-farm income opportunities, plot etc…

13. What the changes in your farming practices have you made in the past 5 years?
14. How has making these changes affected farming for you?
15. Do you expect to maintain these changes?
16. Do you expect to make new changes in response to any of the issues you raised today?
    a. Followup: How will these changes affect farming for you, if they continue?

    Prompts: Crop choice, crop rotation, irrigation methods, investment in technologies, time spent in agriculture, etc…

Appendix 4

Topics and issues of concern reported by farmers during interviews in 2017. Arrows represent causal relationships asserted by farmers between topics.



Appendix 5

Interpretation and analysis of influential APEX parameters for discussion with farmers. Continued on following page.

Model Verification			Development of Drivers, Scenarios, and Questions					
*Influential APEX input parameter**	*Influential process**	*Farmer interpretation of parameter / process*	*Initial / expected condition (from calibrated model)**	*Farmer-reported underlying drivers*	*Modeler interpretation of driver*	*Sample scenario or question*	*Parameters adjusted in model*	*Model prediction categories affected*
Potential heat units (PHU)	Crop growing season	Timing / length of growing seasons	(Crop and location-specific)	Unpredictable weather and climate	Climate variability (temp, wind, humidity, precipitation)	What will happen to crop yields, soil fertility, etc. with continued unpredictable seasonal climate cycles?	Monthly weather station inputs, to generate more variable climate patterns	Crop growth, hydrology, erosion/sedi-mentation, nutrient cycling
Bulk density Aluminum saturation (caused by low pH)	Growth constraints, root growth stress	Crop / root growth problems not attributed to other issues	Level of application of deep tillage and lime to lower BD and raise pH, respectively	Availability and cost of lime Availability and cost of animal-drawn tillage	Lime application rate Usage of deep tillage	How might the application of lime change crop health? Is it worthwhile to hire animals to run a deeper plow on my plot?	Lime application rate in operations schedule Deep tillage in operations schedule	Crop growth, hydrology (percolation and evaporation)
Potential evapo-transpiration (PET) or runoff equation Difference between field capacity (FC) and wilting point (WP)	Water stress: excessive PET or run-off, low plant-available water	Crop wilting; visibly waterlogged soil	Farmer's observation of water stress in crops or water-logged soil Timing and amount of irrigation water or rainfall	Drought events High rainfall events Timing of rainy season	Precipitation variability (amount and timing)	How will the next big drought effect my crops? How much irrigation will I need to do to maintain crop yields? If rains come late (or early), what will be the effect on my soil and crops?	Monthly weather station precipitation inputs, to generate more variable precipitation patterns	Crop growth, hydrology, erosion/sedi-mentation, nutrient cycling
Soil organic N, P, and C Number of years of cultivation at start of simulation Fertilization rates	Nutrient stress: low mineral-ization rates, inadequate fertilization, excessive leaching of N	Plant symptoms: limited leaf growth, yellowing, dead tips of leaves/shoots Low soil organic matter (SOM) Fertilizer application	Farmer's observation of extent or degree of plant symptoms and SOM deficiency Farmer's use of fertilizers Years under cultivation	Availability and cost of fertilizer Availability and cost of manure and other soil amendments	Fertilizer application rate Manure application rate	Is it worthwhile to apply more fertilizer? When and how much? How important is manure in the long-term fertility of my soil and health of crops grown here?	Fertilizer application rate in operations schedule Manure application rate in operations schedule	Crop growth, nutrient cycling

Plant population Maximum potential leaf area index, harvest index, and biomass-energy ratio	Growth and harvest	Plant population Crop stand Harvest volumes	Farmer- and crop-specific	Availability and cost of seeds and seedlings Availability and cost of labor	Planting density	How would a denser planting affect crop growth and yield? Can I increase the amount of harvest by increasing planting density?	Planting density in operations schedule	Crop growth

* Typically influential APEX parameters, processes, and parameter ranges are from Wang et al. 2012. Following verification, initial conditions should fall within suggested parameter ranges. Excluded from this table are categories of influential APEX components for which insufficient data will available for verification with farmers.