Impacts of Small Scale Irrigation on Poverty Dynamics in the White-Volta Basin of Ghana: An Integrated Multi-Agent Simulation Approach

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Abstract

Frequent drought and adverse economic conditions are the major problems faced by the irrigation sector in the semi-arid areas of sub-Saharan Africa. In this paper, a bioeconomic multi-agent system (MAS) was developed to analyze different policy instruments that could improve irrigation farming and reduce rural poverty in the Upper East Region of Ghana. To better quantify the level of poverty and its distribution, the household decision model included a three-stage budgeting system (namely a savings model, a Working-Leser model, and an Almost Ideal Demand System). The agent-based model was applied to a sub-basin of the White Volta River in Ghana and calibrated and validated using survey data collected in 2005. With the help of simulation experiments, we analyze the potential impacts on household welfare and poverty distribution when relaxing the cash constraints and increasing the off-farm income opportunities in the region. Simulation results suggest substantial increases in income and consumption levels of those households that are having irrigation plots but not for poor households cultivating only rainfed plots. The scenario analyses also show increased application rates of mineral fertilizer when households have better access to credit, which may help to restore the sustainability of cropping systems. Our results imply that increasing public investment to provide irrigation plots to the farming community together with more favorable economic incentives might bring about the intended results of poverty reduction as well as diversification of agriculture.

Key words: Agent-based modeling, irrigation farming, access to credit, food security.

Introduction

The emerging climate-change issues, combined with slow increase in food production and declining rate of yield growth in main food crops threaten world food security and livelihoods of millions of poor people in developing countries, especially in Sub-Saharan Africa (von Braun et al., 2008). To achieve the millennium development goals (such as cutting hunger and poverty in half by 2015) much more efforts must be undertaken to increase the productivity in agriculture and the value of products produced, since farming is the mainstay of the rural poor. To reduce the risks associated with rainfall variability and to increase the yields of food crops, more public investments in yield-enhancing technologies—such as small-scale irrigation and irrigation management systems—have been recommended as one important rural development and poverty reduction strategy (Pinstrup-Andersen and Pandya-Lorch, 2001).

Especially in the Northern semi-arid tropics of Ghana—where poverty incidence is very high compared to other regions in the country—the Government of Ghana has undertaken considerable efforts to increase access to irrigation in recent years. Yilma et al., (2008), however, found in econometric analyses that high irrigation levies, increased input prices and lack of credit markets are the major constraints to expanding the area under irrigation. Building on these findings, the first objective of this paper is to analyze the potential benefits on household income, poverty level and area under irrigation when constraints such as shortages of cash and off-farm income can be relaxed. The second objective is to show how the multi-agent model can be used to analyze the distribution of consumption poverty among farm households by including a three-stage budgeting system, containing a savings model, a Working-Leser model, and an Almost Ideal Demand System.

The remainder of this paper is organized as follows: the next section will introduce the linkage between irrigation and poverty alleviation, followed by some background data about the study area, a brief description of the methodology applied, the various components of the multi-agent model and insights into the validation of the model. After that, the paper presents the simulation results and concludes with a short discussion.

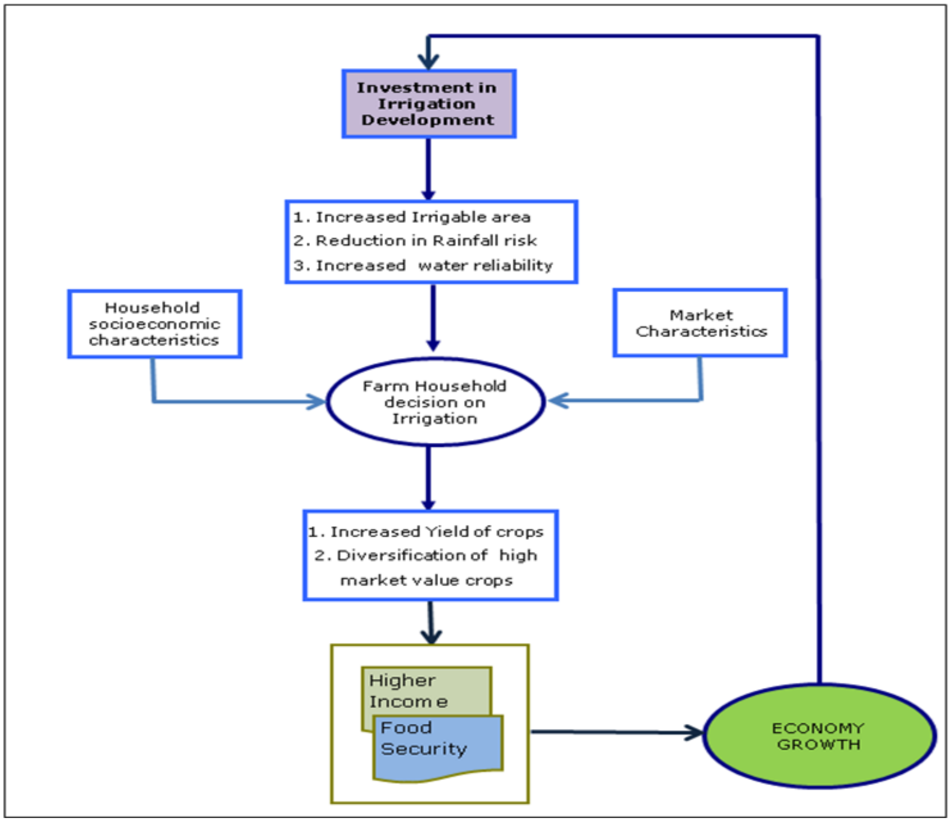
Conceptual framework: Irrigation - poverty alleviation linkage

For countries in sub-Saharan Africa like Ghana where agriculture is the mainstay of the economy, not only economic growth in general but also growth of the agricultural sector in particular is important for poverty alleviation. The adoption of new technological innovations as well as research and development are the major driving forces of agricultural growth (Norton, 2004; von Braun *et al*., 2008). Through direct and indirect effects, adoption of agricultural technologies can help to reduce poverty and malnutrition. Adopters directly gain higher yields and incomes from the new technology, whilst indirect gains are derived from adoption by others leading to lower food prices, employment creation, and growth linkage effects between sectors of the economy (de Janvry and Sadoulet, 2002).

Irrigation farming is one of the most important rural development investments that can have both direct and indirect impacts on poverty and food security in semi-arid tropical countries (IFPRI, 2002; Bhattarai and Narayanamoorthy, 2004). The schematic representation of the causal relationships between irrigation development, farmer incomes and economic growth are depicted in the Figure 1. As Yilma and Berger (2006) showed in their econometric analysis, reliable irrigation increases both crop yields and application of mineral fertilizers, which in turn contributes to higher land productivity and improved incomes of farm households. Irrigation further enables farmers to cultivate non-traditional high value crops, such as tomato, onion, green pepper and leafy vegetables etc. Under favorable economic conditions, farmers can thus diversify their cropping patterns and earn higher incomes, which would increase overall household consumption and reduce poverty levels. Depending on the technology used, irrigation farming demands more labor for construction, maintenance and operational work. Therefore it creates employment opportunities for the non-farming households in the region.

However, simply providing irrigation infrastructure to farm households is not a guarantee that rural poverty and malnutrition are being reduced. In addition to that, an enabling socio-economic environment (like access to roads, markets, credit, training and information about innovations) must be provided to the poor farmers to actually make them engage in irrigation farming.

Figure 1 Irrigation-poverty alleviation linkage



Irrigation in Ghana and problem background

The northern semi-arid tropics in Ghana comprises three regions namely Upper East, Upper West and Northern, which are characterized by an unfavorable biophysical environment with frequent failure and uneven distribution of rainfall, rather poor soil quality and often land degradation. Apart from these adverse biophysical conditions, factors like lack of access to credit and insurance markets, high costs of inputs, and poor economic infrastructure play a significant role for the weak performance of agriculture and high incidence of poverty (GOG, 2003). With the experience of Asia, many SSA countries realized that investment in irrigation infrastructure could be an important poverty alleviation policy, which would boost agricultural productivity and also reduce risks associated with rainfall variability. The government of Ghana, for example, made an effort with the help of foreign donors to rehabilitate existing and construct new irrigation schemes. Currently, there are 22 medium to large irrigation projects in the country, among them the Tono and Vea irrigation schemes located in the Upper East Region (UER), with irrigation areas of 2,490 and 850 ha respectively (Yilma *et al*., 2008). These irrigation projects, however, were rather supply-driven and followed a top-down approach what might explain the limited involvement of local communities and farmers near the project areas. Initially, the state-run irrigation company allocated plots of irrigated land to farmers and supplied them with subsidized inputs, such as fertilizers, insecticides, farm equipment and services. Today, the privatized Irrigation Company of the Upper Region (ICOUR) has to charge irrigation levies from the farmers and cannot anymore provide inputs at a subsidized price (Yilma *et al*., 2008). As a result of unfavorable economic conditions, the profitability of irrigation agriculture is rather low and the irrigation schemes operate below capacity. Especially capital poor farmers are locked out from engaging in irrigation farming.

This paper makes an attempt to develop and apply a multi-agent model to analyze the potential impacts of relaxing various farm-level constraints to irrigation farming. The model is also used to assess which policy instruments (easier access to credit, increased off-farm income and decreased input prices) could give more incentives for participation in irrigation farming, measuring its likely impacts on household livelihoods and overall distribution of poverty level in the region.

Study area

The study area is located in the Upper East Region (UER) of Ghana, which is the poorest among the 10 regions in Ghana (Gyasi et al., 2006). The poverty level of 70% is high compared to the national level of 40%. The UER is relatively densely populated; 104 person per km^2 as compared to the national average of 75 person per km^2 (GSS, 2004). In the following, we outline how the multi-agent model was parameterized.

Mathematical programming based multi-agent system (MP-MAS)[1]

MP-MAS is a multi-agent simulation package developed at Hohenheim University, based on the work by Berger 2001, Schreinemachers et al. 2007 and Berger et al. 2007. The software couples a cellular component that represents the landscape under study with an agent-based component

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[1] MP-MAS is a free software application developed at Hohenheim University and can be downloaded from https://mp-mas.uni-hohenheim.de/

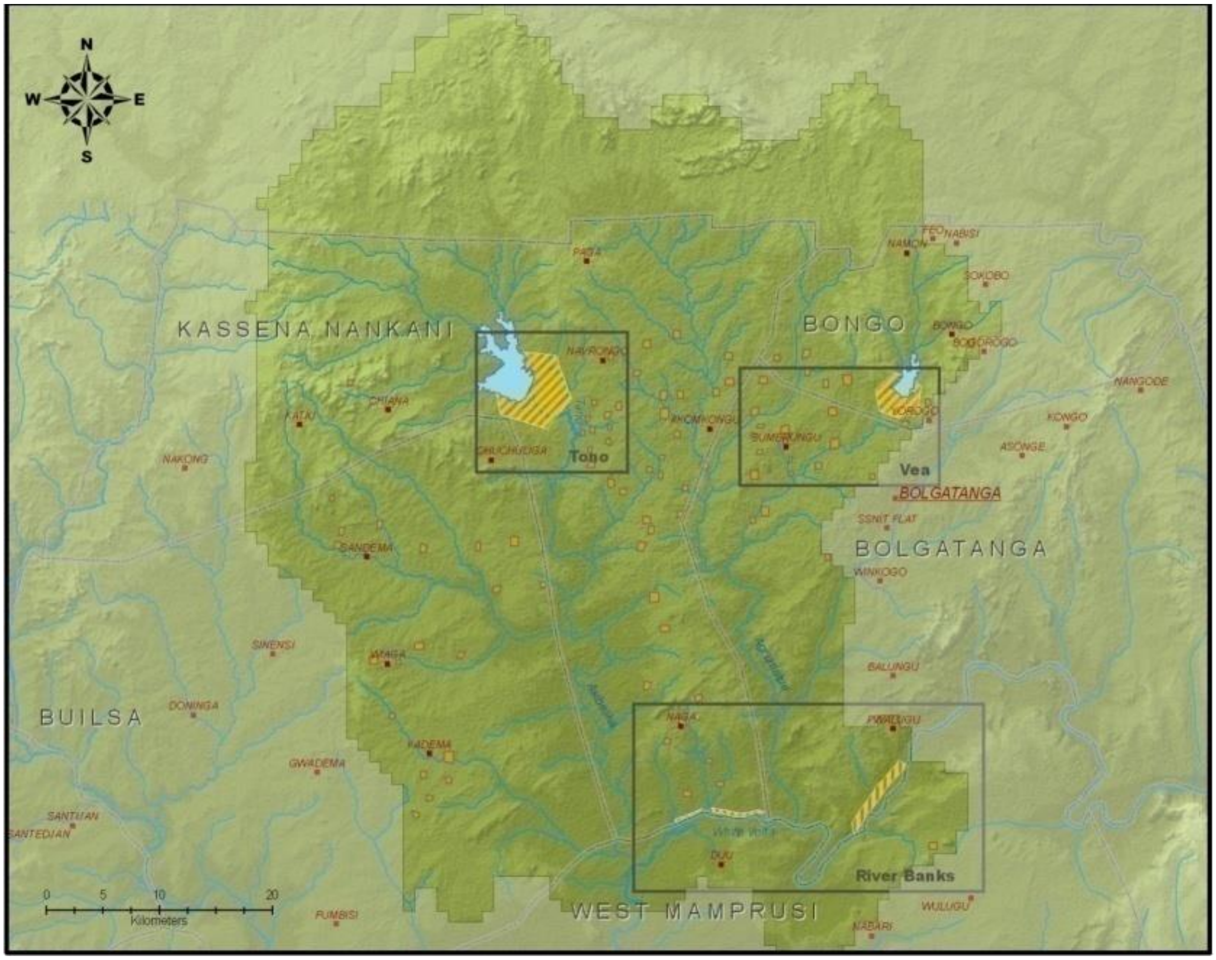
that represents the human decision making. A detailed description of the methods for creating the landscape and agent components can be found in Berger and Schreinemacher (2006).

Components of multi-agent model

The landscape

The study area encompasses the Vea and Tono irrigation schemes and various small reservoirs within a sub-basin of the White Volta River (Figure 1). The farm households in this area are mainly subsistence farmers and grow rainfed crops in the rainy season (April to September) and irrigated crops in the dry season (November to March). The main food crops are rice, millets, groundnut, maize and beans, all rainfed; the main cash crops are tomato, onion and leafy vegetables, which all cultivated in the dry season under irrigation.

Figure 1: Study area in the White Volta basin of Ghana



The spatial information was collected from various sources, for example the GLOWA Volta Project and Water Resources Commission of Ghana. Using the *ArcGIS* software, the farming land in the catchment was netted out by taking out forests, roads, rocky unsuitable lands, areas under water, etc. The location of small reservoirs and the 2 large irrigation schemes in UER, namely Tono and Vea, were plotted on the Map. The exact spatial location of the irrigation command area was unfortunately not available. Based on secondary information, the irrigable land area was therefore hand drawn for each irrigation sites in the catchment; this land represents the irrigable land available for cultivation to the farmers. The remaining farming land constitutes the rainfed land. The landscape in the multi-agent system consists of uniform grid sized cells; a grid cell represents a piece of landscape (0.25 ha) that can be used for agricultural production.

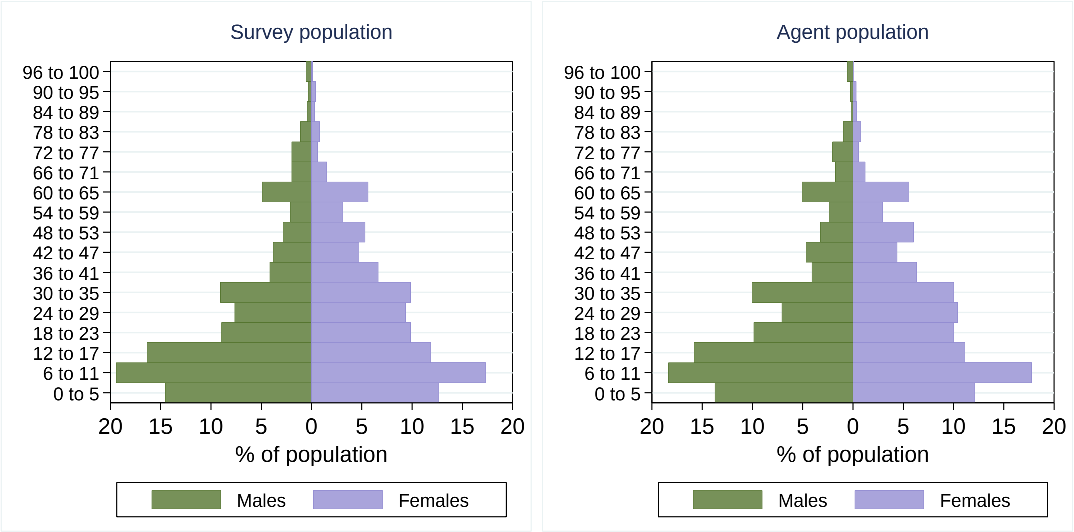
Location of agents and farm plots

Since there was no information available about the location (latitude/longitude) of each household in catchment, a spatial randomization procedure was used to generate the location of all agents and their farm plots. Using survey data collected in all districts of UER during 2005, the sample was divided into 4 clusters based on the number of agricultural plots operated by each household. The number of plots was used to cluster the sample because this was the one variable most strongly correlated with other variables like household size, number of livestock and agricultural implements (assets). For each cluster, the distribution functions for rainfed land, irrigated land, and distance of farming plots to the farmstead were estimated from the survey data. Then using this information, the farmsteads and farming plots were randomly allocated to the agents in the landscape. The study area, for which detailed simulation results will be presented below, finally comprised of 1,609 computational agents (farm households).

Agent population

The socioeconomic layers contain information about the agents' resource distribution and their membership to the network threshold groups. The survey data collected in the UER has 292 sample households, which was a relatively small fraction when compared to actual population in UER. Following Berger and Schreinemachers (2006), a Monte Carlo technique was used to generate a random agent population from our survey data. Cumulative distribution functions for the resources were calculated for each cluster of sample observation. Each agent was allocated quantities of up to 78 different resources using this random procedure. The resources included 68 different categories of household members (34 age and 2 sex groups), 6 types of livestock (goat buck, goat doe, cows, bulls and sheep ewe and sheep ram), female head, liquidity, form of expectation, and innovativeness. In UER, households have a large number of livestock, so a maximum of 20 piecewise linear segmentation was used to implement the empirical distribution functions. Figure 2 compares the population pyramid calculated for the survey population with the pyramid for the agent population. The pyramids more or less look similar in their distribution of members under different age category. The random generator hence created a realistic demographic structure.

Figure 3: Population pyramid comparing survey estimate with agent population



Agent decision model: Mixed integer linear programming (MILP)

Agent decision-making is modeled using mathematical programming (MP)[2]. The MP approach assumed each household to maximize the expected utility (which consists of cash income from sales (crop and livestock products) and off-farm labor, in-kind income from self-consumption of crop and livestock products, and the annuity of future expected income from investments) under constraints such as different types of land, labor, capital, irrigation water, consumption

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[2] The livestock production in the model can only take integer values so the type of mathematical program used is a mixed integer linear program (MILP).

requirements, etc. Due to the presence of market imperfections in the UER, cash income and in-kind home consumption objectives are included separately in the model objective function[3], i.e. the production and consumption decisions of agents are non-separable and must both be taken into account when optimizing land use decisions. The aggregate structure of household decision model is given in Appendix1.

Three-stage non-separable decision process

Based on Berger 2001 and Schreinemachers *et al*. 2007, in this paper a multi-period three-stage non-separable MP was applied. For each year in the simulation, three MILP matrices are being solved for each agent, simulating investment, production and consumption decisions respectively. Each decision involves the optimization of a MP problem, and parts of the solution vectors are transferred between sequential stages. The matrices are agent-specific and differ in terms of internal matrix coefficients (e.g., yields and consumption function coefficients), objective function (e.g., prices), right-hand-side values (e.g., resource endowments, assets and liquid means), and in the number of included constraints. Investment and production decisions are based on expected yields and prices. After the inputs decisions are made in the production decision, the bio-physical model (CROPWAT) simulates crop yields based on the plot-level water deficit. Expected yields of each crop are then replaced by simulated actual yields in the consumption stage matrix, and the final income obtained by the agents is allocated between savings and consumption, depending on the food energy requirement. Even though the model runs at an annual time period, it includes monthly land, labor, and water constraints to capture multiple cropping, peak labor needs and monthly variations in the irrigation water supply. The non-linear responses of the crop yields to different combination of inputs (like labor and fertilizers) were modeled using a piecewise linear segmentation in MP.

To capture the consumption and poverty level in the UER, the consumption part in the model includes a detailed budgeting system that allocates the income from farm and non-farm activities to savings, non-food expenditure (using a modified Working-Leser model), and eight categories of food products (using a Linear Approximation of the Almost Ideal Demand System

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[3] When markets are imperfect, the resource allocation that optimizes the level of income does not necessarily optimize consumption (Sadoulet and de Janvry 1995).

(LA/AIDS)). The Ghana Living Standard Survey (GLSS) IV 1998/99[4] data was used to estimate the savings, expenditure and demand equations for the food categories, which were all included as parameters in MP-MAS. The expenditure values on each food categories were converted into adult equivalent energy units and used to estimate the consumption and poverty level for each agent household.

Simulating crop yields using CROPWAT model

The crop yields were modeled following the FAO 56 approach (Clarke *et al.* 1998, Smith 1992). The crop-water requirement (CWR) for crop *i* in month *m* is the product of a crop coefficient (*Kc*), the potential evapotranspiration (*ET0*), and the planted area (*AREA*):

$$CWR_{i,m} = Kc_{i,m} \times ETO_{m} \times AREA_{i,m}$$

The CWR could either be met through irrigation (IRR) or rainfall. The total rainfall might not be available for crops, so total rainfall was converted into effective rainfall (ERF) to capture the share of rainfall actually available to the crop, depending on its growth stage. Deficit irrigation water (DefWAT) was then calculated as the difference between the crop water requirements and the effective water supply which include effective rainfall and irrigation:

$$DefWAT_{i,m} = CWR_{i,m} - ERF_{i,m} - IRR_{i,m}$$

The crop yield reduction coefficient (Kr) for each crop was defined as:

$$Kr_{i} = \left(\frac{1}{m} \times \sum \frac{DefWAT_{i,m}}{CWR_{i,m}} \middle| \, CWR_{i,m} > 0 \right)$$

To simulate the actual crop yield (*ActYLD*), the *Kr* value of each crop was multiplied by the crop yield potential (*YldPOT*):

$$ActYLD_{i} = Kr_{i} \times YldPOT_{i}, \qquad if \ Kr_{i} \geq 0.5$$

$$ActYLD_{i} = 0, \qquad if \ Kr_{i} < 0.5$$

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[4] The GLSS IV of 1998/99 was the only recent available data set with information on household level consumption expenditures on each food and non-food items, different sources of income, and price data on each food and non-food items at the local market level.

The main source of irrigation water in the study area is surface water and rainfall. The Tono irrigation scheme and 11 small dams are the source of surface water supply. The available irrigation water in each irrigation site (inflow) is then shared among the agents based on their amount of irrigable land in that particular irrigation site.

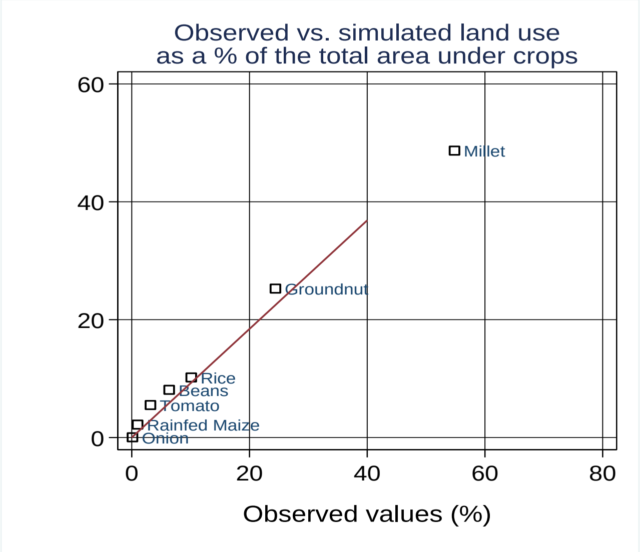
Innovation diffusion

The only type of agent-agent interactions in the model is networks of innovation diffusion. Based on Berger 2001, innovation diffusion was modeled using individual network thresholds. Each agent in each period compares the adoption level in the network with its own threshold; if the first exceeds the second then the innovation becomes accessible to the agent and enters the MILP. The network adoption rate increases when the innovation is adopted by many agents.

Model validation

The MP-MAS model was validated by conducting regression analyses between observed land use values with predicted values from running the baseline scenario (McCarl and Apland, 1986). The baseline reflects the current situation and assumes the current trend in demography, diffusion of innovations, prices and rainfall. A regression line was fitted through the origin for the observed and predicted land use of main seven crops expressed in percentage to total area of these crops. The comparison was done at higher aggregation level (i.e. catchment). The parameter coefficient of 0.92 and explained variance of 0.99 indicates that the model results are identical with the current trend (Figure 4).

Figure 4: Validation of land-use with linear regression fit



Note: Model fit - Coefficient = 0.92; STD Error=0.03; R-squared = 0.99

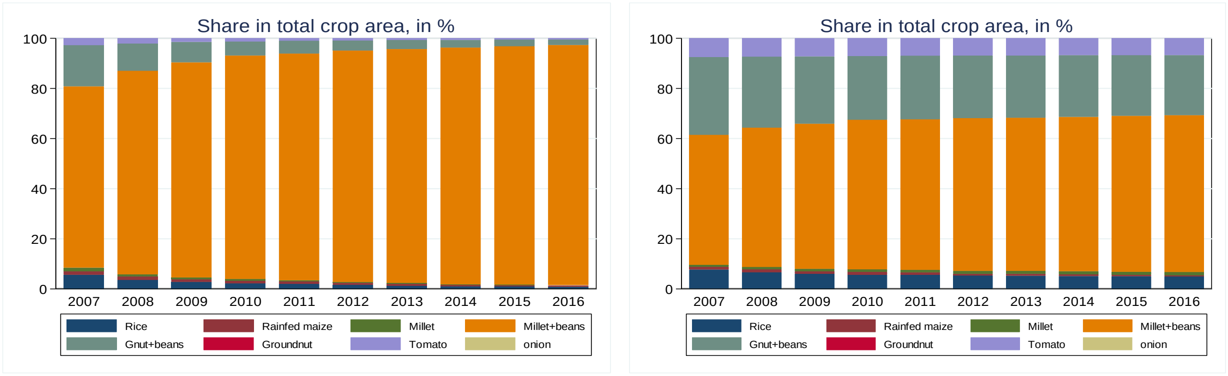
The model results

The baseline model results reflects current land use patterns that are dominated by staple crops (millet and beans) with limited cash requirements and rather low productivity. The irrigation area is not fully cultivated, only 30-40% area under tomato, irrigated rice and onion. The livestock is used as a buffer for smoothening the food consumption demands, and food security is decreasing on average over the simulation period.

Access to credit

To relax the capital constraints, all households in the model are given access to farm credit. Figure 5 shows that access to credit would enable households to change their land use from subsistence rainfed farming to high value crop irrigation farming. Even with 25% of interest rate, the model suggests that households apply for farm credit and expand their area under irrigation farming. The simulation results show that access to credit would likely increase the average household income and food energy consumption (Table 1). The application of mineral fertilizer (in kg per ha) could also triple with the access to credit which would help to improve the sustainability of agricultural land use in the region.

Figure 5: The simulated land use pattern


Baseline

Access to credit

Table 1: Impacts of different scenarios

Scenario	Income (GH. Cedi)	Food Energy Cons. (BJ/Capita)	Avg. Fertilizer (Kg/ha)
Baseline	826.80	2.82	16.50
+ Access to dry season migration	873.34	2.98	17.24
+ Access to credit	1282.19	4.11	53.35
+ Both	1330.95	4.26	54.80

Note: Average value over 10 year simulation period

Table 2: Impact of credit on different farm types

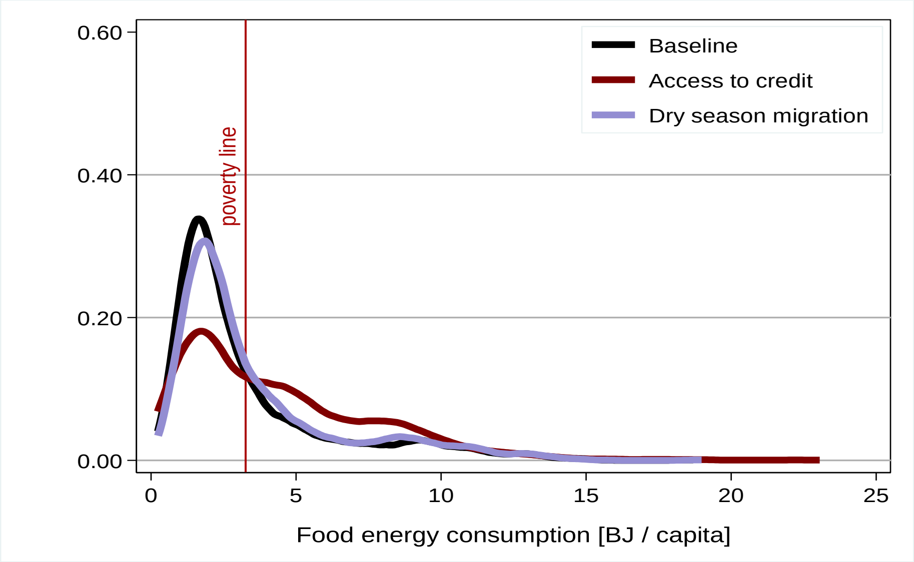
Farm type	Average Income per HH (GH. Cedi)		Change
	Baseline	Access to Credit	
Rainfed farm	620.94	760.42	0.22
Big dam farm	1109.55	2019.21	0.82
Small dam farm	1123.34	1757.25	0.56

Note: Average value over 10 year simulation period.

The impacts of credit on welfare of the different farm types are analyzed and given in Table 2. The simulation results show that access to credit could increase the income of the irrigation farm households (small dam and big dam farms) by 56% and 82 % respectively over the baseline income level, while the income of the rainfed farm households would increase only by 22 %. The results indicate that farm households who have physical access to irrigation land would be benefiting more by availing credit than subsistence rainfed farmers. We conclude from this policy scenario, that providing access to credit without expansion of irrigation facilities in the region would not give the intended result of improving the livelihood of poor subsistence rainfed farmers.

The kernel density distributions of poverty for different scenarios are given in the Figure 5. Access to credit would probably reduce poverty substantially, as most of the poor households could cross the poverty line (3.259 BJ/capita/year). The distribution graph also shows that the poorest agents would not benefit from access to credit, as the tail of the distribution has not changed. This is mainly because the poorest agents are those without physical access to irrigation land and availing credit for rainfed farming is not so profitable. So the poverty status of the poorest agents would probably not change even under favorable policy interventions.

Figure 5: Kernel density graph showing the change in poverty distribution

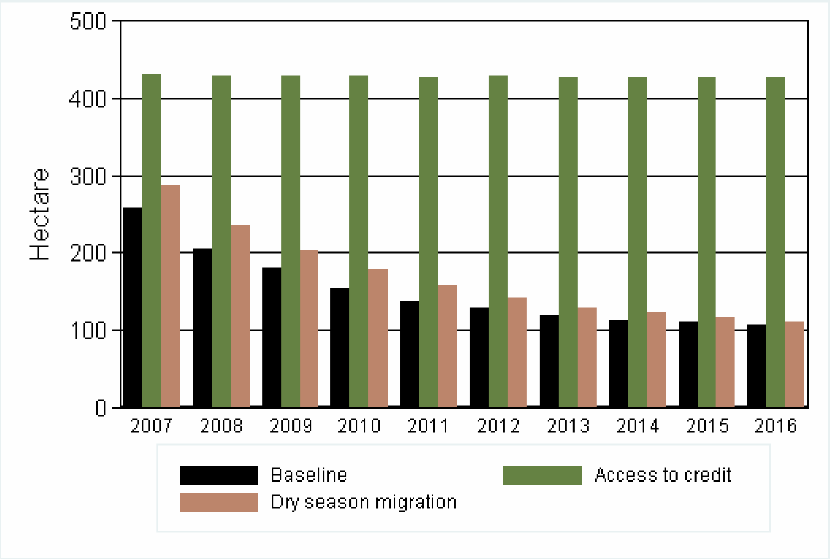


Access to dry season migration (off-farm income)

In UER, due to imperfect credit markets, the capital required for irrigation farming in the dry season is financed through off-farm income sources like dry season migration to nearby town, small trading, charcoal burning, and off-farm labor. The econometric study by Yilma et al., 2008 revealed that dry season irrigation farming and off-farm income are complementary to each other even though both activities are taking place in the same season. The multi-agent model is used to analyze the impacts of access to dry season migration on irrigation farming in the UER. The scenario assumed that the number of persons migrating from each household should not exceed more than two persons.

The simulation results showed that the access to dry season migration has marginally increased the income of the farm households compared to baseline income (Table 1). The results also indicate that the income from off-farm employment is utilized to finance irrigation farming, which is evident from the increase in the total area under irrigated crops when compared to the baseline scenario (Figure 6). The results indicate that in the presence of market imperfections, the cash-constrained households in UER use their labor force off-farm to finance the irrigation farming.

Figure 6: Irrigated area (in ha) under different scenarios



Conclusion

In this paper, a bioeconomic multi-agent model was developed and used to analyze various policy instruments that can improve the income from irrigation farming and thereby reduce rural poverty in the UER of Ghana. The household survey analyses and econometric studies conducted in the UER revealed that most farm households are cash constrained—since the early 1980s there is no government support for rural credit and agricultural input markets. On the "business-as-usual" path, the simulation results suggest that the cash constrained farm households would not have enough incentives to extend the capital intensive irrigation farming and could only continue subsistence rainfed farming. The results also indicate that under this condition food security in the region would further deteriorate. By providing farm households access to credit, the simulation experiments show considerable positive effects on both household income and poverty distribution; however, one must keep in mind that so far market and price risks have not been fully accounted for. Simulation results also suggest that access to credit could promote capital intensive irrigation farming and much higher levels of fertilizer application. The model results clearly show that farm households who have access to irrigation land are receiving higher benefits than rainfed farm households.

The results underline the need to rethink the current policy focus in Northern Ghana: more instruments should be tested for provision of credit and increased public investment in order to improve the physical access of irrigation land for poor farm households, which might bring the intended results of poverty reduction as well as diversification of agricultural production in the region.

Acknowledgement

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References

Berger, T., 2001. Agent-Based Models Applied to Agriculture: A Simulation Tool for Technology Diffusion, Resource Use Changes and Policy Analysis. *Agricultural Economics.* 25(2/3), 245-260.

Berger, T., Schreinemachers, P., 2006. Creating Agents and Landscapes for Multiagent Systems from Random Samples. *Ecology and Society,* 11 (2): 19. [online] URL: http://www.ecologyandsociety.org/vol11/iss2/art19/

Berger, T., Schreinemachers, P., Arnold, T., 2007. Mathematical Programming-Based Multi-Agent Systems to Simulate Sustainable Resource Use in Agriculture and Forestry. A software manual. Hohenheim University.

Bhattarai, M., Narayanamoorthy, A., 2004. Impact of Irrigation on Agricultural Growth and Poverty Alleviation: Macro Level Analysis in India, Research Report 12, IWMI, Colombo. Srilanka.

Clarke, D., Smith, M., El-Askari, K., 1998. CropWat for Windows: User Guide. University of Southampton.

de Janvry. A., Sadoulet, E., 2002. World Poverty and the Role of Agricultural Technology: Direct and Indirect Effects. *Journal of Development Studies* 38(4): 1-26.

GSS (Ghana Statistical Survey). 2004. Ghana Living Standard Survey Report (GLSS 4), 1998/99. Accra, Ghana.

Government of Ghana (GOG)., 2003. Ghana Poverty Reduction Strategy (GPRS) 2003-2005. An Agenda for Growth and Prosperity, Accra: Ghana.

Gyasi, O., Schiffer, E., and McCarthy, N., 2006. Community Needs Assessment and Local Water Governance Appraisal in the Upper East Region, Ghana. Draft, Submitted to EPTD Discussion Paper, International Food Policy Research Institute, Washington DC, USA.

IFPRI., 2002. Green Revolution Curse or Blessing? Washington DC, USA.

Janssen, S.J.C., Van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. Agricultural Systems 94, 2, 622-636.

McCarl, B.A., Apland, J., 1986. Validation of Linear Programming Models. *Southern Journal of Agricultural Economics.* December, 155-164.

Norton. R. D., 2004. Agricultural Development Policy – Concepts and Experiences. Food and Agricultural Organization of the United Nations. Wiley, England.

Pinstrup-Andersen. P., Pandya-Lorch. R., 2001. Agricultural Growth is the Key to Poverty Alleviation in Low-Income Developing Countries. In: Pinstrup-Andersen P. and Pandya-Lorch R. (Eds.). The Unfinished Agenda. Washington DC: International Food Policy Research Institute.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. *Annals of the Association of American Geographers.* 93(2), 314-337.

Sadoulet, E., de Janvry, A., 1995. Quantitative Development Policy analysis, The John Hopkins University Press: Baltimore, London.

Schreinemachers, P., Berger, T., Aune, J.B., 2007. Simulating Soil Fertility and Poverty Dynamics in Uganda: A Bio-Economic Multi-Agent Systems Approach. *Ecological Economics.* 64(2), 387-401.

Smith, M., 1992. CROPWAT, A Computer Program for Irrigation Planning and Management. *FAO Irrigation and Drainage paper.* 46.

von Braun, J., Fan, S., Meinsen-Dick, R., Rosegrant, M.W., Pratt, A.N., 2008. International Agricultural Research for Food Security, Poverty Reduction, and the Environment: What to Expect from Scaling Up CGIAR Investments and “Best-Bet” Programs. IFPRI Report. Washington, DC: International Food Policy Research Institute.

Yilma, T., Berger, T., 2006. Complementarity between Irrigation and Fertilizer Technologies – A Justification for Increased Irrigation Investment in the Less-Favored Areas of SSA, Paper presented at the International Association of Agricultural Economist Conference, Gold Coast, Australia.

Yilma, T., Berg, E., Berger, T., 2008. The Agricultural Technology-Market Linkage under Liberalization in Ghana: Evidence from Micro Data. *Journal of African Economies*. 17, 62-84.

Appendix 1 Aggregate structure of household decision model

Constraint	Grow Rainfed crops	Grow Irrigated crops	Invest in new livestock	Maintain livestock	Sell crops	Sell Livestock	Consume own food	Purchase food	Hire in labour	Hire out labour	Purchase inputs	Short-term credit	Deposit cash	Income transfer	Food expenditures	Food consumption	Food energy needs	Sell produce in future	Sign	**RHS**
Objective Function					**+C**	**+C**	**+C**		**-C**	**+C**	**-C**	**-C**	**+C**					**+C**		**MAX**
Rainfed Land (ha)	+1																		≤	B
Irrigated Land (ha)		+1																	≤	B
Labour (man-days)	+A	+A	+A	+A					-1	+1									≤	B
Water (liters/sec)		+A																	≤	B
Livestock (head)			-1	+1		+1													≤	B
Cash (GH. Cedi)											(+C)	-1	-1						≤	B
Variable inputs (Kg)	(+A)	(+A)									(-1)								≤	B
Current Yield (Kg)	(-Y)	(-Y)	(-Y)	(-Y)	+1	+1	+1												≤	0
Future Yield (Kg)			(-Y)	(-Y)														+1	≤	0
Income identity (GH. Cedi)							+C		-C	+C	-C	-C	+C	-1					=	0
Total Expenditures														+A	-1				=	0
Food Expenditures															+A	-1			=	0
Food Consumption							-C	-C								+A			=	0
Food energy Balance							-A	-A									+1		≤	B
Food energy requirement (BJ)																	+1		=	0

Notes: C=Price coefficients; A =Technical coefficients; Y=Crop and Livestock yields; B=Available resource endowment. The values in the brackets are adjusted inside the model.