Agrekon

Agricultural Economics Research, Policy and Practice in Southern Africa

ISSN: 0303-1853 (Print) 2078-0400 (Online) Journal homepage: www.tandfonline.com/journals/ragr20

An economic risk analysis of fertiliser microdosing and rainwater harvesting in a semi-arid farming system in Tanzania

Lutengano Mwinuka, Khamaldin Daud Mutabazi, Stefan Sieber, Jeremia Makindara & Jean-Claude Bizimana

To cite this article: Lutengano Mwinuka, Khamaldin Daud Mutabazi, Stefan Sieber, Jeremia Makindara & Jean-Claude Bizimana (2017) An economic risk analysis of fertiliser microdosing and rainwater harvesting in a semi-arid farming system in Tanzania, Agrekon, 56:3, 274-289, DOI: 10.1080/03031853.2017.1343154

To link to this article: https://doi.org/10.1080/03031853.2017.1343154

AGREKON, 2017
VOL. 56, NO. 3, 274–289
https://doi.org/10.1080/03031853.2017.1343154

An economic risk analysis of fertiliser microdosing and rainwater harvesting in a semi-arid farming system in Tanzania

Lutengano Mwinuka[a], Khamaldin Daud Mutabazi[b], Stefan Sieber[c], Jeremia Makindara[b] and Jean-Claude Bizimana[d]

[a]The University of Dodoma (UDOM), Department of Economics and Statistics, Dodoma, Tanzania; [b]Sokoine University of Agriculture (SUA), School of Agricultural Economics and Business Studies, Morogoro, Tanzania; [c]Leibnis Centre for Agricultural Landscape Research (ZALF) e.V., Institute for Socio-Economics, Müncheberg, Germany; [d]Texas A&M University, Department of Agricultural Economics, Agricultural Food and Policy Center, Tamu, USA

ABSTRACT

This paper attempts to relate farm-level technologies in a semi-arid area with economic viability, taking risk analysis into consideration. Data gathered from various sources, such as a household baseline survey, farm trials, agricultural experts and government agencies, were used. Crop yields, crop prices, and prices for key production inputs, mainly fertiliser and rainwater harvesting through tied-ridges, were simulated for the net economic return distributions, e.g., pearl millet, groundnuts, and sunflower under different farm-technologies scenarios using a farm simulation model. The results indicate that an intercrop of pearl millet and groundnuts is the most economically viable farming system compared with other alternative scenarios if supplemented with rainwater harvesting technology. Risk neutral and risk-averse farmers both prefer this approach. If these technologies are geographically considered and synthesised, they may be cost-effective for farmers with implications for the current and future livelihood and productivity of crops in rural semi-arid areas.

KEYWORDS
Economic risk; semi-arid farming system; fertiliser microdosing; rainwater harvesting; farm simulation model

JEL CLASSIFICATION
O13; O31; O33; Q12

1. Introduction

Farmers in semi-arid areas of Sub-Saharan Africa (SSA) face vast challenges in terms of securing food and alleviating poverty, while simultaneously ensuring environmental sustainability (Reynolds *et al.*, 2007; Makurira *et al.*, 2011). Inadequate access to, and use of, soil nutrients along with water shortages and drought substantially compromise production of food crops in these areas (Sanchez, 2002; Reynolds *et al.*, 2015). Common responses to these production constraints, such as applying chemical fertilisers and harvesting rainwater, often pose environmental risks and have economic implications in terms of costs and returns for crops (Mwinuka *et al.*, 2016). The environmental and productivity-related impacts of land-use decisions are not only direct, but also systemic and cyclical in nature (Bommarco *et al.*, 2013). Consequently, interventions directed at minimising or eliminating the environmental impact of crop production can have positive implications throughout current and future crop production cycles and in locations far from their origin. However, smallholder farmers in SSA are not responding to land constraints through a process of intensification, involving multiple cropping during the year and adoption of synthetic fertilisation techniques (Camara *et al.*, 2013; de Graaff *et al.*, 2011).

CONTACT Lutengano Mwinuka ✉ mwinuka.lutengano@gmail.com
This article has been updated since publication on 13 July 2017. Please see the correction statement for more information (DOI:10.1080/03031853.2017.1358910)

The alarming need to produce more food with less investment in key resources, especially land and water on small-scale rain-fed agriculture (Uphoff, 2012; Mwinuka *et al.*, 2016), make it urgent to upgrade current semi-arid farming systems in order to improve rural livelihoods (Rockström *et al.*, 2009; Mwinuka *et al.*, 2015a). As other researchers point out, drought and water shortages represent significant challenges to crop yields and reduce viable cropping areas (de Fraiture *et al.*, 2010; Li *et al.*, 2011). Mwinuka *et al.* (2015a) systematically identify and summarise existing agri-food value chains upgrading strategies (UPS), such as fertiliser microdosing and in-situ rainwater harvesting (RWH) technologies that manage the environmental risks on crop systems. Thus, efficient RWH UPS can address water constraints to crops to a certain extent, but the shortage and depletion of surface water are growing problems (Ali *et al.*, 2009; Wada *et al.*, 2010). Other UPS, for instance fertiliser microdosing, can revitalise soil fertility, as the continuous production of a crop with limited fertiliser inputs contributes to the depletion of soil nutrients in farming systems (Cobo *et al.*, 2010; Camara *et al.*, 2013).

Despite their importance to food security in semi-arid areas of SSA, there are relatively few studies on crops like millets and sorghum. These low-input crops can also contribute to cycles of detrimental environmental impacts and threaten current and future food production (Reynolds *et al.*, 2015). In Tanzania, like other SSA countries, the effects of soil nutrient mining may be especially severe due to socio-economic circumstances and limited technical options that prevent adequate replenishment of nutrients in depleted soils (Vanlauwe *et al.*, 2010; Shiferaw *et al.*, 2011; Mourice *et al.*, 2014). How farmers adapt to various changes and how they ensure better crop production will ultimately depend on the adoption of better farm technologies, such as fertiliser microdosing and RWH (Page *et al.*, 2010; *Mahoo et al., 2012*; Camara *et al.*, 2013). Semi-arid farming systems for key crops, like millets, suffer from a dearth of empirical research (Reynolds *et al.*, 2015). However, a diverse group of small-grain annual cereal grasses, including pearl millet, bulrush millet, finger millet, and several others (sorghum and millets) are particularly important for smallholder farmers on marginal lands that are prone to drought. These crops are typically the primary food crop in dry rain-fed systems on poor soils with minimum synthetic inputs (*Burke et al., 2009*; Msongaleli *et al.*, 2015).

In this regard, there is a need to develop low-input soil fertility management practices for those cereal crops with high economic potential that are primarily grown in the semi-arid areas of Tanzania, such as Dodoma (Graef *et al.*, 2014; Msongaleli *et al.*, 2015; Mwinuka *et al.*, 2015b). As the rainfall season is frequently short and intense in regions growing sorghum and millet, problems like water runoff and soil erosion are major yield constraints (*Murty et al., 2007*; Msongaleli *et al.*, 2015). As the debate continues over whether adding fertiliser to the soil is beneficial or not (Gilbert, 2012), the objective of this paper is to assess the economic viability of implementing fertiliser microdosing and RWH technologies at the farm level in the semi-arid area of Tanzania. Fertiliser microdosing and RWH are not just valuable options for increasing crop productivity, but they are also an ideal entry point to gain the trust and confidence of farmers (Fox *et al.*, 2005; Kristjanson *et al.*, 2012; Camara *et al.*, 2013). In our case, fertiliser microdosing involved deep fertiliser placement of one bag of DAP-18 per cent N, 46 per cent P_2O_5 (di-ammonium phosphate) per hectare, i.e., 25 per cent of recommended rates, instead of spreading fertilisers evenly across the field at larger rates (Camara *et al.*, 2013). Whereby, in-situ RWH using tied-ridges harvests rainwater directly as it falls on the field, or collecting and concentrating runoff water within fields, with the simultaneous reduction of soil erosion; the tied-ridges have cross-ties made every few metres across the contour furrow (Mahoo *et al.*, 2012).

So far, there is limited knowledge regarding the economic returns distribution and the effects of combining fertiliser microdosing and RWH technologies (Mourice *et al.*, 2014). Precise estimates of risk in association with economic returns on farm-level technologies in semi-arid areas are scarce (Fox *et al.*, 2005; Reynolds *et al.*, 2015). Thus, it is important to relate farm-level technology to economic viability when taking risk analysis into consideration (Richardson *et al.*, 2007; Asci *et al.*, 2015; Mwinuka *et al.*, 2016). Unlike earlier simulations of net returns, we develop empirical distributions of profits (farm-level economic models) associated with fertiliser microdosing and RWH on pearl millet, sunflower, and groundnut as potential crops in the study area. A separate economic analysis is vital for assessing the likely returns on investments in farm-level technology (Farquharson *et al.*, 2013; Leonardo *et al.*, 2015). We hypothesise that integration of fertiliser microdosing and RWH is an economically viable farm technology in semi-arid areas of Tanzania under a rain-fed farming system; thus there is a net increase in economic surplus resulting from the farm technologies. Therefore, this paper contributes to the body of knowledge in this area.

2. Theoretical and Conceptual Background

We make the strong assumption that participatory selection of viable farm-level technologies is vital and, if implemented by potential stakeholders, these will benefit all participants in the agri-food value chain, including farmers, agribusiness, and other agents. A simple theoretical basis is that: farmers in semi-arid areas, as economic agents, always seek to maximise profit by efficiently combining inputs and other resources; in this regard, the combination of a certain level of fertiliser and RWH technologies to maximise profit. For instance, farmers who apply these farm-level technologies are likely to be better-off in terms of productivity, hence profiting more than those who do not adopt these technologies. The paper uses this theoretical background as a guide and integrates key points derived from the theories to build a farm simulation economic model of a semi-arid farming system. This background is considered relevant and underpins the theoretical foundation of the study.

2.1 Farm-level technologies selection

Farm-level technologies used in this paper were prioritised and selected based on a participatory process (Mwinuka *et al.*, 2015a), placing food-insecure smallholder farmers and other key stakeholders at the heart of solutions for addressing root causes of food insecurity (Graef *et al.*, 2014; Ville *et al.*, 2016). The process of selecting these technologies reflects their role in addressing key constraints and their potential linkages to the other components of the agri-food value chains. Identifying the constraints facing farmers and their farming systems are important for guiding farmers' decisions regarding their farm-level technology choices. On the basis of local stakeholders definition on food security with rain-fed farming (Mwinuka *et al.*, 2015b), this study puts emphasis on farm-level technologies, such as fertiliser microdosing and tied-ridges (RWH) for addressing soil moisture stress and depletion of soil fertility.

2.2 Productive efficiency

Farm-level technology is typically considered to be output-increasing (Pfister *et al.*, 2005). In other words, it should result in greater output, given a certain level of input. In our case, a combination of fertiliser microdosing and tied-ridges (RWH) as new technologies that farmers can adopt to achieve a higher production function. Consequently, based on production theory, farmers will not only increase their technical efficiency and food security, but also operate on higher profit frontier function. However, incorporating risk to simulate economic return distribution of new farm-level technologies for better decision-making is vital (Mwinuka *et al.*, 2016). For a robust forecast and decision-making analysis, it is important for economic viability studies to integrate risk (Richardson *et al.*, 2007).

2.3 Simulation and risk mainstreaming

The management of the semi-arid farming system to meet diverse requirements of the farm household is normally exposed to risk. For instance, crop planting and fertiliser applications are undertaken based on limited knowledge regarding the nutrient status of the soil (Archer *et al.*, 2003). It is worth noting that risk and uncertainty are part of many decisions particularly for players involved in the agriculture sector. Moreover, risk is defined as an imperfect knowledge where the probabilities of the possible outcomes are known while uncertainty exists where these probabilities are not known (Richardson & Bisimana, 2017). Smallholder farmers in semi-arid areas of Tanzania are highly vulnerable to yield variability and have limited capacity to protect themselves against price risk (Arce, 2015). Keeping this in mind, yield and input/output prices or market risks are carefully thought out in this paper, excluding institutional, human, and financial risks; these are described in Hardaker *et al.* (2004a). Risk analysis is carried out through a simulation process that results in a large number of simulated values for key output variables (KOVs) of interest to the decision makers (Richardson, 2010). The simulated values for a KOV represent an empirical estimate of the probability distribution for the variable and quantify the risk associated with the variable (Figure 1).

As we strive to build a stochastic model for estimating economic viability of fertiliser microdosing and tied-ridges (RWH), the model includes at least one stochastic (random) variable. Stochastic variables, such as prices and yields, cannot be controlled (Vose, 2002). The stochastic simulation is made to further estimate the unknown probability distribution for a KOV, in our case, net economic returns and/or net present value, so as to facilitate better choices among alternative decision possibilities (Richardson *et al.*, 2008). The probability distribution of these stochastic variables were included to obtain more robust simulation results, instead of drawing conclusions based on a single or deterministic value (Law & Kelton, 2000; Richardson, 2010). Thus, risk was incorporated in our decision where

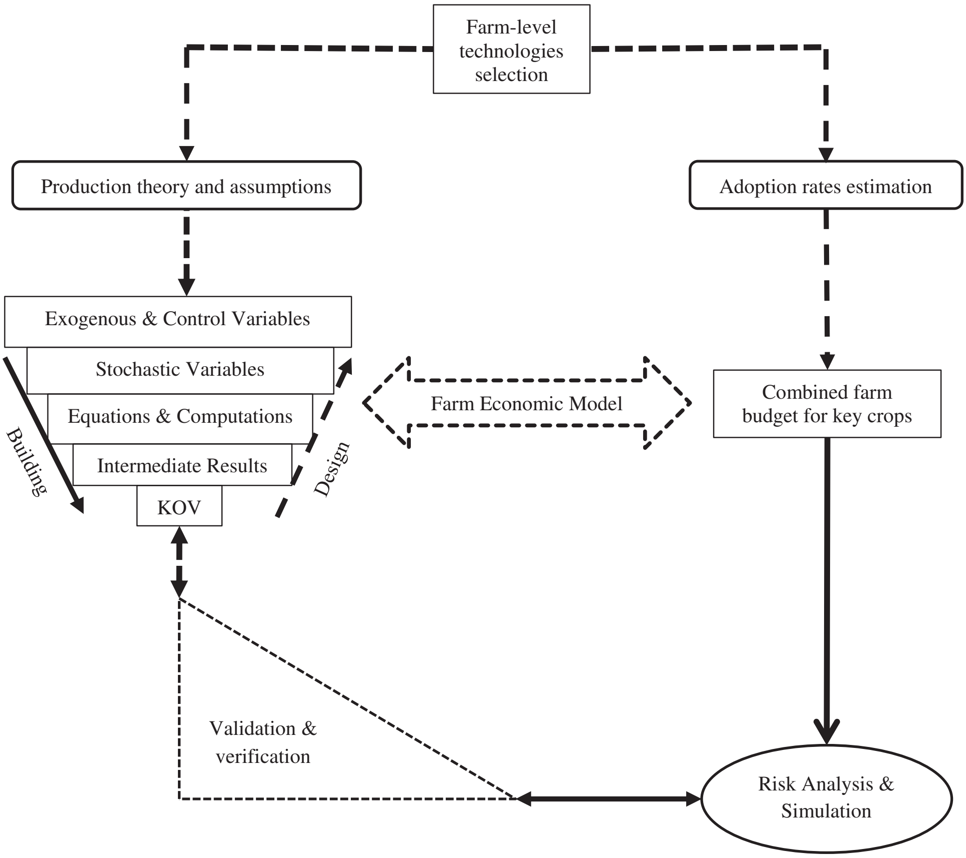

Figure 1. Simulating farm economic returns of fertiliser microdosing and rainwater harvesting (modified from Mwinuka *et al.*, 2016 and Richardson, 2010).

we selected between fertiliser microdose and tied-ridges (RWH) scenarios for different three crop combinations.

3. Methods

3.1 Study area

This study was carried out within the framework of the Trans-SEC (Trans-SEC – Innovating Strategies to Safeguard Food Security Using Technology and Knowledge Transfer: A People Centred Approach) project on upgrading food security in one semi-arid village in Tanzania. Therefore, we benefited from the project's household baseline survey and the farm trials that were implemented by farmers over two consecutive production seasons within the village. This study was undertaken in Idifu village, which is located in the Chamwino district of the Dodoma region, Tanzania. The village has diverse food systems and knowledge gained from the area can easily be transferred to other locations within Tanzania, thus benefiting other villages (Graef *et al.*, 2015). The climatic condition in Dodoma is predominantly semi-arid with low to medium levels of productivity (Mwinuka *et al.*, 2015b). The food system in Chamwino district is mainly based on pearl millet, sorghum, groundnuts, and sunflower (Mutabazi, 2013; Table 1). The district has a total area of 9203.64 km^2 and is situated at a latitude of 6°15′ (6.25°) South and longitude of 35°42′ (35.7°) East, with an average elevation of 1,226 metres (4022 feet).

3.2 Main crops selection process

The agri-food value chains components, including key components, were quickly mapped in a participatory way for the study area. An inventory of upgrading strategies was prepared and prioritised, involving potential stakeholders (Mwinuka *et al.*, 2015a). Based on Mwinuka *et al.* (2015b) and given the set of criteria and weight-based assessment performed, the main crops were selected. Compared with others, these crops have higher impact scores for the features associated with food security, poverty, and sustainability, as well as its impact on the structure of the chain (Table 1). Moreover, the crop selection process was initiated by farmers, who provided their views on the local meaning of food security. Local definitions of food security rely on food availability components, with, for instance, pearl millet showing great potential (Mwinuka *et al.*, 2015b). In this regard, local

Table 1. Dodoma local stakeholders main crop scores based on impacts (modified from Mwinuka *et al.* 2015b).

		Sub-sector/crop				
Type of impact	Criteria	Pearl millet	Sorghum	Groundnuts	Sunflower	Sesame
Food security, poverty and sustainability	Direct contribution to FS	5.0	2.5	4.5	4.0	3.0
	Future potential	5.0	3.5	5.0	4.0	4.0
	# of poor households involved in the sector	5.0	4.5	5.0	2.0	3.0
	Average	5.0	3.5	4.8	3.3	3.3
Structure of the chain	Extent of value adding potential (stability, profitability)	2.5	1.5	2.5	5.0	1.0
	# of different products produced	2.0	2.0	3.0	5.0	1.0
	Length of marketing chain (# of intermediaries)	2.5	2.5	5.0	3.0	4.0
	Marketing potential	1.0	1.5	4.5	3.0	5.0
	Potential for lessons learned/ replication mechanism	4.0	3.5	5.0	5.0	5.0
	Average	2.4	2.2	4.0	4.2	3.2
	Overall average	3.7	2.9	4.4	3.8	3.3

Notes: # represents number, a score of 1 meaning that the particular commodity did not meet that criteria (minimum compliance), and a score of 5 meaning that the commodity best met that criteria (maximum compliance).

stakeholders in Idifu village prefer farm inputs related upgrading strategies, such as fertiliser microdosing and RWH, to improve soil fertility for major food/cash crops like pearl millet and groundnuts (Mwinuka *et al*., 2015a, b). A total of five major crops with high scores were used to represent a semi-arid farming system (Table 1). Using data derived from the household baseline survey, the combination of these crops form a significant share of the farm budget in Idifu; therefore we chose to use them in this study.

3.3 Data sources and key variables

This study uses four main data sources: (a) household baseline data; (b) water and nutrient limited calibrated yields; (c) marginal costs and yields from farmers' field trials; and (d) other useful information based on experts' knowledge, historical data, and field visits. For the purpose of the paper, we used the aforementioned sources to gather useful input to facilitate the analysis. Different sources of information, including historical data, can be used to establish a stochastic simulation of net economic returns or net present value (NPV) (*Richardson et al., 2007*; Vorotnikova *et al*., 2014; Asci *et al*., 2015). This is not an optimisation study; rather, it is a simulation study showing what could occur if fertiliser microdosing and RWH are adopted with different crop combinations. We advance the application developed by Richardson *et al*. (2008) by simulating the distribution of yields and farm economic returns using data from the field trials and the baseline survey.

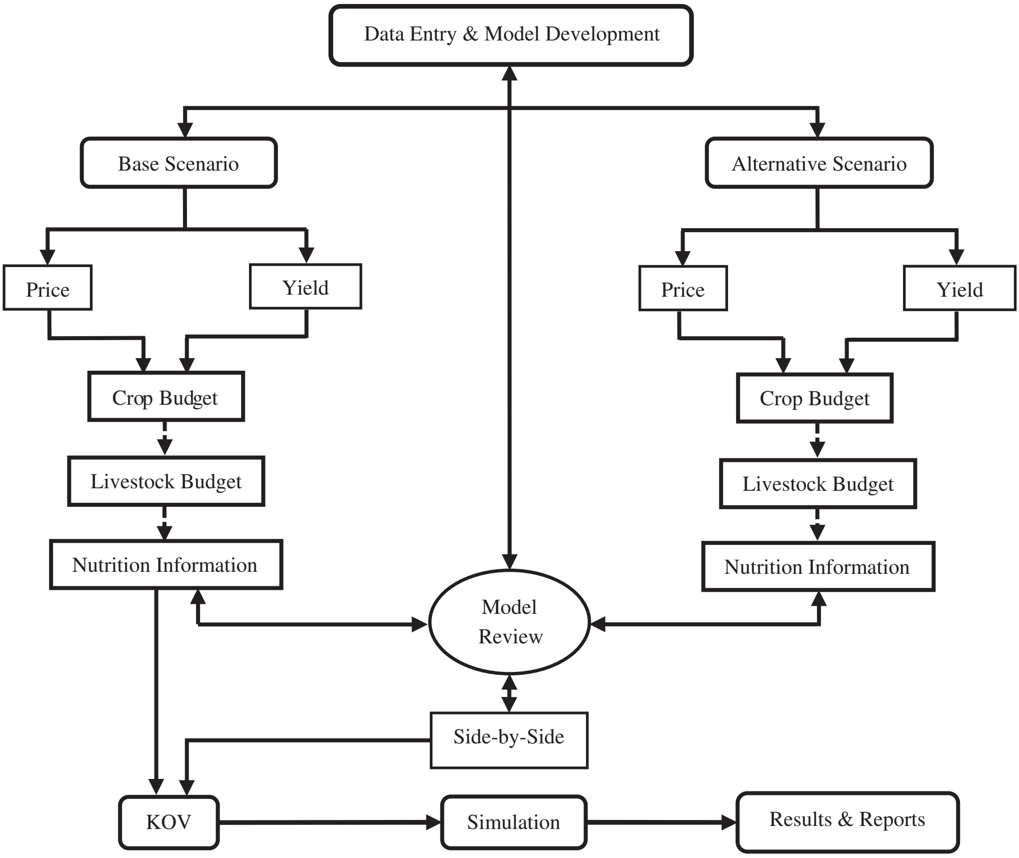

Figure 2. Simplified economic and nutritional impact assessment model development process (modified from Richardson & Bizimana, 2017).

Fundamental variables and required data inputs for a partial farm budget were carefully gathered (Figure 2) to simulate the economic viability of the micro fertilisation technique and RWH under the assumption that these farm technologies would be adopted by semi-arid farmers in the selected village in Tanzania.

The average production costs for major crops grown by farmers (Table 1) and other inputs for partial farm budgets were obtained from the household baseline survey, which reached 150 farmers from Idifu village. The establishment of minimum, average, and maximum values of crop produces prices and yields distributions for incorporating risks were supported by local experts' knowledge and key informant interviews. Risks inclusions eliminate point estimates through probability distributions of KOVs using GRKS distribution (Richardson *et al.*, 2007; Rezende & Richardson, 2015). Other costs for land and labour were not included because they are influenced by multiple and often unknown factors, such as discounts, taxes, etc. (Henry *et al.*, 2011). The resulting marginal costs and yields due to fertiliser microdosing and RWH were collected from a total of 48 farmers' field trials. Thus, net returns in the analysis for capturing the impact of these farm technologies are the difference between farming with and without fertiliser microdosing and rainwater harvesting. Nutritional related information and impacts as part of the model are not presented in the model to save space (Figure 2).

3.4 Data analysis and Monte Carlo simulations

A Microsoft Excel Add-in, SIMETAR, which is a simulation and econometric tool that can analyse risk (Richardson *et al.*, 2008), was used to compute the farm economic returns distributions from adopting fertiliser microdosing and RWH farm technologies. The analysis was completed using the farm economic and nutritional simulation model (FARMSIM), which is supported by SIMETAR (Richardson & Bisimana, 2017). This model is used to simulate a representative farm that uses fertiliser microdosing and RWH as upgrade strategies to secure food production and sale in a village. KOVs of interest were simulated for five years using multivariate empirical distributions (MVEs) of stochastic market prices and yields of the main representative crops (Table 1) in semi-arid farming system. MVEs estimates are very powerful and recommended in situations where standardised probability distributions are limited due to an inadequate number of observations (Richardson *et al.*, 2000). As empirical distributions allow the data to define the shape by themselves, it is more suitable than other distribution forms. Steps for testing economic viability based on a Monte Carlo simulation were followed to reflect the suggestions of Richardson (2010) and Richardson and Bisimana (2017) and consolidated with a few improvements, such as inclusion of forecasted adoption rates, as illustrated in Figures 1 and 2.

Following the organisation of the simulation model, the separation of random and non-random components for all key variables is vital, as stressed by Richardson *et al.* (2008). With the aid of powerful systematic approaches embedded in SIMETAR, random values were simulated 500 times following the Latin Hypercube procedure, resulting in a stochastic distribution of KOVs. Minimum, midpoint, and maximum values for the GRKS distribution option in FARMSIM were computed from the baseline survey and historical information supported with data authentication by local agricultural experts. We decided to use the assortment of MVEs as future yields, crop prices, and farm input costs would change due to inconsistent historical data. Here, we assumed that using different data types provided the proper representation of the historical and future NPV and Net Cash Farm Income (NCFI) of fertiliser microdosing and RWH technologies. Different associated approaches in net returns and risks simulations were noted and are well documented (Fox *et al.*, 2005; Archer and Reicosky, 2009; Henry *et al.*, 2011; Vorotnikova *et al.*, 2014; Asci *et al.*, 2015).

To estimate the differing economic returns due to a switch from simple water and nutrient limited yields to that of fertiliser microdosing application and established RWH, we compare the NPV distributions of scenarios that include and/or exclude these farm-level upgrading strategies for the three selected key crops (Table 2). NPV was estimated by discounting the profits; a 10 per cent discount rate was used. To estimate profit/NCFI, revenue was first calculated by considering production as a

Table 2. List of scenarios selected for economic viability assessment.

Crop 1	Crop 2	Farm system	Farm technology	Label
Pearl millet	Groundnuts	Sole	Flat cultivation with no tied-ridges (RWH) and no fertiliser microdosing	A
Pearl millet	Nil	Sole	Tied-ridges (RWH) without fertiliser microdosing	B
Pearl millet	Nil	Sole	Tied-ridges (RWH) with fertiliser microdosing	C
Pearl millet	Groundnuts	Intercrop	Tied-ridges (RWH) without fertiliser microdosing	D
Pearl millet	Groundnuts	Intercrop	Tied-ridges (RWH) with fertiliser microdosing	E
Sunflower	Nil	Sole	Tied-ridges (RWH) with fertiliser microdosing	F

product of yield and price multiplied by the total farm harvested land area. In our case, we used total land area used to grow main crops (Table 1), including pearl millet, groundnuts, and sunflower, in the representative village. Next, total costs were estimated as a sum of both variable and fixed costs. Based on the nature of the study, for the fixed costs we included marginal fixed costs due to fertiliser microdosing and/or establishment of tied-ridges (RWH) as well as other operating costs associated with transportation and/or fertiliser access. Variable costs primarily included harvest costs and other operating costs, such as land preparations. Other operating costs were associated with pack and sell costs, assuming the situation that the harvested crops reach the markets. Operational costs were highly correlated with the total amount of crop produced; therefore, harvest costs were also assumed to be proportional to yields. These costs were multiplied by total land area to obtain estimated total costs. Thus, for the production season, profit/NCFI was calculated using Equation (1). Distributions of simulated NPV of net returns were generated using Monte Carlo simulations for 500 iterations (Equation (3)). Major crops grown by farmers in the village were taken as part of the partial farm budgeting approach used; however, farm level changes in terms of marginal output and costs were assumed to affect only three crops; specifically, pearl millet, groundnuts, and sunflower (Table 2).

$$NCFI_t = \tilde{T}Rec_t - \tilde{T}Cost_t \tag{1}$$

where, $\tilde{T}Rec_t$ and $\tilde{T}Cost_t$ are the simulated total cash receipts and total costs in year t for crops and livestock (local chicken), respectively.

Probability of positive NCFI was calculated for each year t over the 500 iterations as:

$$P(NCFI_t) = \sum_s (1 \ if \ NCFI_{ts} > 0, \ \ 0 \ else)/500 \tag{2}$$

$$\begin{aligned}\tilde{N}PV = +[\sum_t (\text{Family Living Expenses}_t + \tilde{V}\text{alue Farm Products Consumed}_t) \times (1/(1+DR)^t] \\ - \text{Present Value of Ending Net Worth}\end{aligned} \tag{3}$$

where, Present Value of Ending Net Worth is obtained by multiplying Net Worth_5 and $(1/(1+DR)^5$, while DR is the discount rate to convert future values to present year values. It is worth noting that development of FARMSIM was based on numerous equations, as presented in detail by Richardson and Bisimana (2017).

Exploiting the power of SIMETAR, different alternatives were compared over the defined combination of main crops used in the analysis versus respective farm technologies (Table 2). Vorotnikova *et al.* (2014) propose combining approaches and modelling of market risks to reflect the variability of crop yields and prices. With the aid of graphical presentations, the FARMSIM model was used to present different options that can guide the decision-making process and the efficiency of the fertiliser supply chains. In our case, we used the same output price scenarios; what would happen to the net returns after changing the crop yields, which resulted from a respective fertiliser microdosing rate and RWH technology? Moreover, a new procedure for ranking risky alternatives that is stochastic efficient with respect to a function (SERF) was used. The technique is based on scenarios certainty equivalents (CE) for absolute risk aversion coefficients (ARACs) (Richardson, 2010). Simultaneous, rather than pairwise, comparison of risky alternatives is allowed by the SERF method (Hardaker *et al.*, 2004b). Graphical presentations of SERF results are not only used to facilitate the presentation of ordinal rankings of scenarios but also to assist decision makers with different risk attitudes. Risk premiums may also be readily calculated using the SERF method (risk neutral) to 0.0068 (strong risk averse), as adopted by Mwinuka *et al.* (2016). With the support of SIMETAR, the upper ARAC value was calculated using the following formula proposed by Hardaker *et al.* (2004b):

$$ARAC_w = {}^{r_r(w)}\!/_{w} \tag{4}$$

where $r_r(w)$ is the relative risk aversion coefficient with respect to wealth (w). Anderson and Dillon (1992) proposed $r_r(w)$ to be set equal to 4 (very risk averse). Beginning Net Worth was calculated based on the respective net returns means from a total of six scenarios used in this paper (see Table 4 later).

3.5 Farm-level economic model verification and validation

Stochastic simulation implies a different way of approaching scientific research. Economic models and micro-level simulations are in urgent need for informing decision-making (Fontana, 2005). Simulation shows that better understanding and explanation of economic facts can be gained and grasped (Richardson *et al.*, 2007). However, each stochastic simulated model must be validated for its completeness, accuracy, and forecasting ability. As highlighted by Richardson (2010), key variables used to compute the KOVs, such as yields, prices and variable costs, were checked to verify that they were conformed to theoretical expectations. Side-by-side output Microsoft Excel sheets of the farm economic simulation model (FARMSIM) were reviewed and verified given appropriate properties of the parent data inputs and distributions (Figure 2). More importantly, the Student *t* tests for means and correlation coefficients included in SIMETAR of the two counterparts series, such as historical data and simulated values, were tested. The test results failed to reject that parameters of the compared series are statistically the same at the 95 per cent level.

4. Results and Discussion

4.1 Net returns of farm technologies to cropping systems

Summary statistics of the simulated net economic returns to crops after employing tied-ridges (RWH) and fertiliser microdosing are presented in Table 4, supported by simulated yields and prices in Table 3. Five-year averages of simulated returns to main crops due to tied-ridges (RWH) and fertiliser microdosing technologies are slightly higher compared with the control situation (without technologies) with exception of scenario C. Moreover, the overall economic return for scenario D is larger than the rest of scenarios (Table 4). Upgrading crop production by using tied-ridges (RWH) on intercrop of pearl millet and groundnuts is more cost-effective and results in significantly higher net returns with a relatively small coefficient of variation (CV) of yields compared with other alternatives.

Relative viability of returns to key crops under the five scenarios, as measured by the coefficient of variation (Table 4), is more than 50 for most of them, except for scenario D, which has CV of 38.3. The results show that if farmers adopt scenario D, they will have larger profits and have less relative risk compared with other scenarios. This scenario (D) also has the highest return on investment and, therefore, can offset addition costs emanating from the establishment of tied-ridges. Scenario D has the highest probability of net returns greater than zero than to other alternative scenarios (Table 4).

Table 3. Summary of the statistics of simulated yields and prices.

Variable	Mean	SD	CV	Minimum	Maximum
Baseline scenario (A)					
Pearl millet yield (kg ha^{-1})	552.8	553.4	100.1	39.4	1683.0
Sorghum yield (kg ha^{-1})	537.8	586.1	109.0	0.0	1704.7
Groundnuts yield (kg ha^{-1})	342.0	391.5	114.5	0.0	1146.3
Sunflower yield (kg ha^{-1})	465.7	169.4	36.4	184.5	732.0
Sesame yield (kg ha^{-1})	1037.9	609.0	58.7	31.3	2000.0
Alternative scenarios (B to F)					
(B) Pearl millet yield (kg ha^{-1})	831.56	605.43	72.8	66.3	1881.0
(C) Pearl millet yield (kg ha^{-1})	1060.40	622.60	58.7	157.0	2159.5
(D) Pearl millet yield (kg ha^{-1})	526.00	32.50	6.2	473.5	578.5
(D) Groundnuts yield (kg ha^{-1})	358.60	92.30	25.7	209.0	507.5
(E) Pearl millet yield (kg ha^{-1})	974.50	301.40	30.9	508.0	1481.5
(E) Groundnuts yield (kg ha^{-1})	377.80	84.90	22.5	239.5	514.0
(F) Sunflower yield (kg ha^{-1})	875.10	891.10	101.8	151.0	2761.0
Crop prices					
Pearl millet price (USD kg^{-1})	0.56	0.33	58.5	0.06	1.06
Sorghum price (USD kg^{-1})	0.68	0.58	86.0	0.01	1.57
Groundnuts price (USD kg^{-1})	2.27	0.87	38.1	1.07	3.72
Sunflower price (USD kg^{-1})	1.46	1.58	108.3	0.21	4.60
Sesame price (USD kg^{-1})	2.84	0.31	11.0	2.44	3.39

Notes: A = baseline scenario (flat cultivation with no tied-ridges (RWH) and no fertiliser microdosing, B to F are alternative scenarios, whereby, B = tied-ridges (RWH) without fertiliser microdosing on pearl millet (sole), C = tied-ridges (RWH) with fertiliser microdosing on pearl millet (sole), D = tied-ridges (RWH) without fertiliser microdosing on pearl millet and groundnuts (intercrop), E = tied-ridges (RWH) with fertiliser microdosing on pearl millet and groundnuts (intercrop), and F = tied-ridges (RWH) with fertiliser microdosing on sunflower (sole), SD = standard deviation, CV = coefficient of variation. Base and alternative yields for crops representing a farming system with exception of scenarios (B to F) are the same (Table 1 and Table 2).

Figure 3 presents cumulative distribution functions (CDF) of the simulated scenarios (A–F). Based on the common axis of simulated NPV values, estimation of unobservable distributions show large chance of getting relatively higher NPV value for the alternative scenario F, however, the probability range from 2 per cent to 86 per cent for getting highest NPV favour scenario E compared with others (Figure 3).

4.2 Net cash farm income and economic risks assessment for scenarios

Certainty equivalents for the alternative scenarios are presented for various ARAC values by upgrading strategy in Figure 4. Certainty equivalents are simply equal to the mean (expected) net return when ARAC is equal to zero, but decline as ARAC values become larger; that is, as risk aversion increases. Thus, scenario D provides the highest certainty equivalents for all realistic risk aversion coefficients (Figure 4). The result indicates that scenario D is preferred by all risk neutral and risk

Table 4. Five years averages of simulated net returns for a control and upgraded alternative scenarios.

Variable (USD ha^{-1})	Mean	SD	CV	Minimum	Maximum	Probability (NCFI > 0)
A-control/baseline	83.00	59.65	72.3	(17.74)	366.82	0.98
B-tied-ridges (RWH) without fertiliser microdosing on pearl millet (sole)	86.04	82.73	96.6	(40.94)	479.94	0.93
C-tied-ridges (RWH) with fertiliser microdosing on pearl millet (sole)	52.13	62.67	124.8	(66.62)	339.19	0.80
D- tied-ridges (RWH) without fertiliser microdosing on pearl millet and groundnuts (intercrop)	120.61	45.29	38.3	23.68	318.39	1.00
E-tied-ridges (RWH) with fertiliser microdosing on pearl millet and groundnuts (intercrop)	98.46	48.80	51.8	(7.63)	310.01	0.99
F-tied-ridges (RWH) with fertiliser microdosing on sunflower (sole)	85.22	71.61	85.7	(32.84)	452.17	0.94

Notes: SD = standard deviation, CV = coefficient of variation, NCFI = net cash farm income, and RWH = rainwater harvesting.

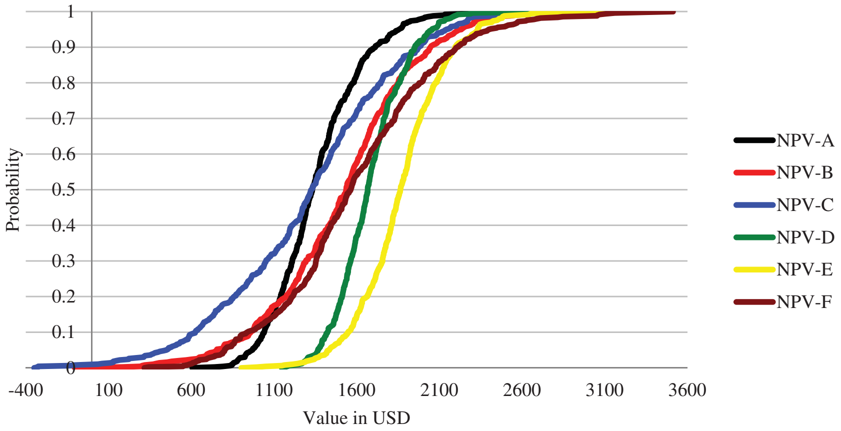

Figure 3. Cumulative distribution function (CDF) of the net present value for base (NPV-A) and alternative scenarios (NPV-B to F).
Notes: Elaborations of scenarios (A to F) was presented using Table 2 and Table 4.

averse decision makers over all the other scenarios tested. Excluding scenario D, the certainty equivalents are initially larger for scenario B than for scenario A at ARAC values ranging from 0 to 0.0034. Scenario B was found to have less certainty equivalents than scenario F when crosses ARAC value of 0.0068. These certainty equivalents at different ARAC value levels imply that semi-arid farmers with a slight aversion to risk and those with a strong aversion to risk would tend to prefer intercropping pearl millet and groundnuts with tied-ridges (RWH) without using fertiliser microdosing.

The Stoplight charts in Figure 5 summarise the stochastic results on NCFI for baseline and alternative farm technologies scenarios. The charts show probability of getting less than 38 USD and more than 116 USD net returns in year one of stochastic simulation, given different farm-level technologies. Establishment of lower and upper cut-off values using the average of all scenarios at the 25 per cent and 75 per cent quantiles, respectively, were used for comparison purposes (Richardson, 2010). The chart shows that there is a 19 per cent chance that annual NCFI is less than 38 USD for the baseline

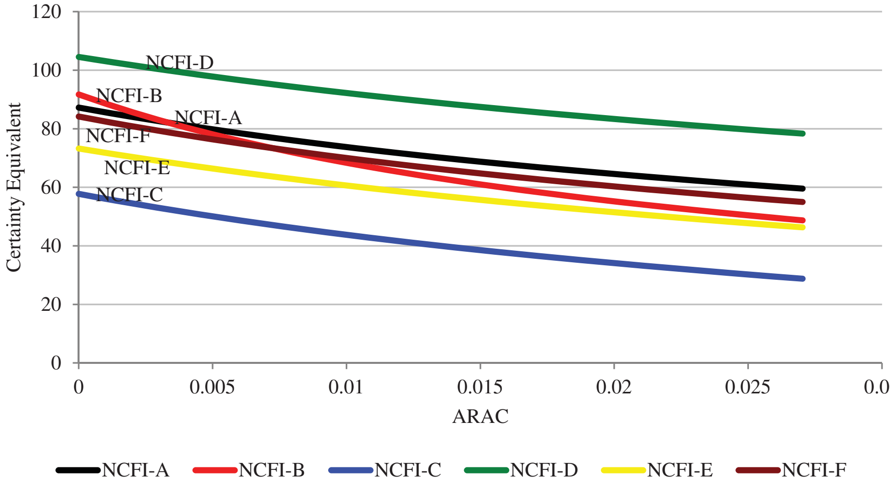

Figure 4. Stochastic efficiency with respect to a function (SERF) under a negative exponential utility function of NCFI in year one of stochastic simulation.

Notes: ARAC represents absolute risk aversion coefficient, and NCFI represents net cash farm income. Scenario D is over the others and results are consistence for SERF of NPV.

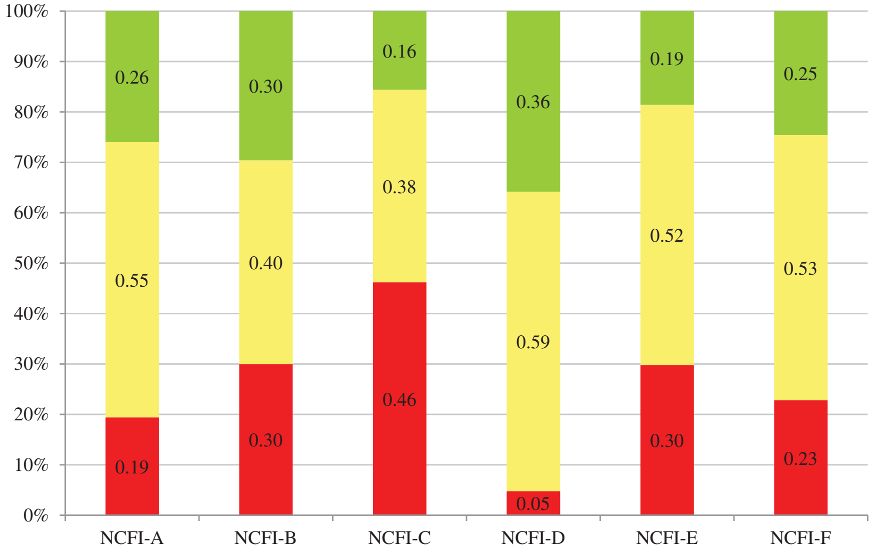

Figure 5. Stoplight charts for probabilities less than 38 USD and greater than 116 USD for different crops and farm technologies scenarios in year one of stochastic simulation.

Note: NCFI represents net cash farm income for all scenarios, and USD represents United States Dollar currency. A to F scenarios for farmers using different of crops and farm technologies are presented in Table 2.

case. Whereby, the chance of annual NCFI being below 38 USD for scenario B is 30 per cent, scenario C is 46 per cent, scenario D is 5 per cent, scenario E is 30 per cent, and scenario F is 23 per cent.

Under the alternative scenarios, the probability of annual NCFI exceeding 116 USD is the highest (36 per cent) for scenario D. The simulated distribution of annual NCFI across five years (Table 4) is more favourable for the scenario D and it is consistence with SERF results; hence it can pull farmers out of poverty and secure food supplies. Farmers, as decision makers, would make significant returns if they invest and move from the baseline scenario to scenario D, followed in second place by scenario F (Figure 5).

Alternative scenarios were assessed on the basis of the simulation model. Economic theory enhanced the better understanding of the approach. We went further by re-running the simulation model (FARMSIM) for various farm-level technologies. In this regard, in using a probabilistic approach to risk analysis, we forecast not only expected net returns but also the range of possible outcomes for NPVs, if tied-ridges (RWH) and fertiliser microdosing were adopted by farmers in semi-arid regions. It was noted that powerful instinctive features of SIMETAR, tractability of GRKS, and empirical distributions can result in a viable farm-level economic model that informs the decision-making process (Richardson, 2010; Mwinuka *et al.*, 2016).

Elaborations using the three main crops in a semi-arid area and combination of micro fertilisation techniques with RWH through tied-ridges can be very informative to farmers and other decision makers (Asci *et al.*, 2015). These alternative scenarios were considered to simulate stochastic crop prices and yields. A focus on risks to crop production, which addresses the farming system in semi-arid areas, is needed (Reynolds *et al.*, 2015). Detailed economic analysis in this area offers better contributions to the limited studies that integrate natural resources management practices, as most rely on agronomic issues (Tabo *et al.*, 2005; *Twomlow et al., 2010*; Asci *et al.*, 2015). In sustaining food production, various measures are required, including intensify farming, rebuilding soils, increasing rainwater use efficiency, and promoting low-cost technologies that farmers can control and afford (Kristjanson *et al.*, 2012; Turinawe et al., 2015). In-depth discussion with potential stakeholders, particularly farmers and agricultural experts, can offer better insight into the production and market conditions for both inputs and crops produced, hence lending more credence to the data and greater confidence of the results.

Higher economic returns of scenario D were fairly influenced by RWH technology, as it reduces the level of environmental risk to productivity (Dar & Gowda, 2013). Farmers in semi-arid areas can easily adopt an RWH upgrading strategy with or without combining it with micro fertilisation technology, as moisture is a bigger problem for them (Aune & Bationo, 2008). In this regard, farmers can abandon the use of fertiliser if rainfall conditions are not conducive for their farming system (Fufa & Hassan, 2006). It was also noted that RWH through tied-ridges is currently the best way to stop or slow down runoff for upgrading crop undergrowth in semi-arid areas, leading to increased food crop production (Fox *et al.*, 2005; Akroush & Dhehibi, 2015). A combination of fertiliser microdosing and tied-ridges (RWH) can increase the productivity and profit of important crops, such as sunflower, under sole cropping system. However, the economic benefits are likely to be greater for other crops in semi-arid areas if management of the crops, soil fertility, and soil moisture is improved.

5. Conclusion and Implications

This paper strives to contribute to the production economics, agronomic, and semi-arid areas farming literature by integrating the risk impacts of crop yields, crop prices, as well as prices of fertilisers and establishment of tied-ridges. The article assesses the profitability and risk efficiency of fertiliser microdosing and rainwater harvesting through tied-ridges for the typical semi-arid farming system of Tanzania. Stochastic variables, such as crop prices, yields, and expenses, were simulated and used to assess the economic returns of these farm-level technologies relative to water and nutrient limited scenarios. Generally, the intercropping of pearl millet and groundnuts in semi-arid areas of Tanzania was found to be important for the farming system. Potential economic gains can be seen when this farming system is complemented with rainwater harvesting technology. Sunflower can be upgraded for greater yields and profit if supplementing fertiliser microdosing with rainwater harvesting. In this regard, increased production due to fertiliser technology can further be enhanced by improving the fertiliser supply chain, hence favourable prices of this farm input to farmers.

The results show differences in stochastic economic returns between the water and nutrient limited (base) scenario and those with fertiliser microdosing and rainwater harvesting (tied-ridges). The intercrop system between pearl millet and groundnuts applying tied-ridges without fertiliser microdosing is more profitable compared with other alternative scenarios. Net returns variability increase as farmers complement tied-ridges with fertiliser microdosing and our result is consistent with others that show risk-averse farmers would prefer a limited number of technologies suiting their environment than those who are risk-neutral. The use of micro fertilisation techniques under farmers' conditions to different crops in semi-arid areas was not economical, resulting in smaller net returns. It would be more cost-effective if farmers use rainwater harvesting technologies and exploit multiple welfares by intercropping pearl millet and groundnuts. Tied-ridges can reduce environmental-related risks, thereby increasing not only productivity of important crops in semi-arid areas but also profits and rural livelihoods.

Better extension services and acquainting farmers with user-friendly technologies for making ridges, for instance, use of a plough supported by animal power in semi-arid areas, can facilitate the prompt adoption and further diffusion of this farm-level technology. Moreover, the use of both trials and data from real farm settings reinforce the findings of the paper. However, the analysis uses fertiliser prices, which are stochastic, and farm input levels were held constant across years. Adjustment of farm input levels based on price changes over time would be helpful.

The semi-arid area of Dodoma has depleted soils hence farmers were unable to gain significant economic returns from the pearl millet, groundnuts and sunflower yield gains due to fertiliser microdosing application and rainwater harvesting technology. Therefore, better understanding is needed of the possible marginal yield and income responses across all agro-ecological zones of Tanzania before investing in soil moisture and soil nutrient technologies. Future studies should also assess the economic return distributions of farm technologies for different crops combinations in sub-humid areas for a clear depiction of the impact to the other farming systems.

Acknowledgements

We thank the farmers for their hard work and dedication in testing the upgrading strategies at the case study site. The authors gratefully acknowledge researchers who developed SIMETAR and made it available to facilitate study simulations and decision-making. Lutengano Mwinuka is very grateful to various people and institutions through the United States Agency for International Development (USAID) – Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI) project, all contributing in one way or another towards the successful completion of his three-month stay at Texas A&M University. This publication is a product of the Trans-SEC project (www.trans-sec.org). The German Federal Ministry of Education and Research (BMBF) funded the project, co-financed by the German Federal Ministry for Economic Cooperation and Development (BMZ). The views expressed are those of the authors' and may not in any circumstances be regarded as stating an official position of the BMBF and BMZ.

References

Akroush, S. and Dhehibi, B. 2015. Predicted willingness of farmers to adopt water harvesting technologies: A case study from the Jordanian Badia (Jordan). *American-Eurasian Journal of Agricultural & Environmental Sciences* 15(8): 1502–1513.

Ali, M.Y., Waddington, S.R., Timsina, J., Hodson, D. and Dixon, J. 2009. Maize-rice cropping systems in Bangladesh: Status and research needs. *Journal of Agricultural Science and Technology USA* 3(6): 35–53.

Anderson, J.R. and Dillon, J.L. 1992. *Risk analysis in dryland farming systems*. Farming Systems Management Series No. 2. Rome: Food and Agriculture Organisation.

Arce, C.E. 2015. *Agricultural sector risk assessment: Tanzania*. Washington, DC: World Bank Group Report 94883 (Tanzania).

Archer, D.W., Pikul Jr, J.L. and Riedell, W.E. 2003. Analyzing risk and risk management in cropping systems. In *Dynamic Cropping Systems: Principles, Processes, and Challenges*, eds Hanson, J.D. and Krupinsky, J.M., 155–164. Bismarck, ND: Northern Great Plains Research Laboratory.

Archer, D.W. and Reicosky, D.C. 2009. Economic performance of alternative tillage systems in the northern Corn Belt. *Agronomy Journal* 101: 296–304.

Asci, S., Borisova, T. and VanSickle, J.J. 2015. Role of economics in developing fertiliser best management practices. *Agricultural Water Management* 152: 251–261.

Aune, J.B. and Bationo, A. 2008. Agricultural intensification in the Sahel - the ladder approach. *Agricultural Systems* 98(2): 119–125.

Bommarco, R., Kleijn, D. and Potts, S.G. 2013. Ecological intensification: harnessing ecosystem services for food security. *Trends in Ecology & Evolution* 28(4): 230–238.

Burke, M.B., Lobell, D.B. and Guarino, L. 2009. Shifts in African crop climates by 2050, and the implications for crop improvements and generic resources conservation. *Global Environmental Change* 19: 317–325.

Camara, B.S., Camara, F., Berthe, A. and Oswald, A. 2013. Micro-dosing of fertiliser–a technology for farmers' needs and resources. *International Journal of AgriScience* 3(5): 387–399.

Cobo, J.G., Dercon, G. and Cadisch, G. 2010. Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agriculture, Ecosystems & Environment* 136(1): 1–15.

Dar, W.D. and Gowda, C.L.L. 2013. Declining agricultural productivity and global food security. *Journal of Crop Improvement 27*: 242–254.

de Fraiture, C., Molden, D. and Wichelnsa, D. 2010. Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. *Agricultural Water Management* 97: 495–501.

de Graaff, J., Kessler, A. and Nibbering, J.W. 2011. Agriculture and food security in selected countries in sub-Sharan Africa: Diversity in trends and opportunities. *Food Security* 3: 195–213.

Farquharson, R.J., Martin, R.J., McCorkell, B., Scott, J.F., Sotheary, E., Phaloeun, C. et al. 2013. Characteristics of an agricultural innovation and incentives for adoption: Rhisobium in Cambodia. *International Journal of Environmental and Rural Development* 4(2): 44–39.

Fontana, M. 2005. *Computer simulations, mathematics and economics*. Working Paper 06. Department of Economics, University of Turin, Italy.

Fox, P., Rockström, J. and Barron, J. 2005. Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. *Agricultural Systems* 83: 231–250.

Fufa, B. and Hassan, R.M. 2006. Determinants of fertiliser use on maize in Eastern Ethiopia: A weighted endogenous sampling analysis of the extent and intensity of adoption. *Agrekon* 45(1): 38–49.

Gilbert, N. 2012. African agriculture: Dirt poor. *Nature* 483: 525–527.

Graef, F., Schneider, I., Fasse, A., Germer, J.U., Gevorgyan, E., Haule, F. et al. 2015. Natural resource management and crop production strategies to improve regional food systems in Tanzania. *Outlook on Agriculture* 44(2): 159–167.

Graef, F., Sieber, S., Mutabazi, K., Asch, F., Biesalski, H.K., Bitegeko, J. et al. 2014. Framework for participatory food security research in rural food value chains. *Global Food Security* 3(1): 8–15.

Hardaker, J.B., Huirne, R.B.M., Anderson, J.R. and Lien, G. 2004a. *Coping with risk in agriculture*. Wallingford, UK: CABI Publishing.

Hardaker, J.B., Richardson, J.W., Lien, G. and Schumann, K.D. 2004b. Stochastic efficiency analysis with risk aversion bound: A simplified approach. *The Australian Agricultural and Resource Economics Journal* 48(2): 253–270.

Henry, R.S., Johnson, W.G. and Wise, K.A. 2011. The impact of a fungicide and an insecticide on soybean growth, yield, and profitability. *Crop Protection* 30: 1629–1634.

James, D.J. 2015. *Adoption and use of Web 2.0 technologies: A comparison of four adoption models as a case study of a state government eExtension project*. Published thesis submitted to the Faculty of Business, Education, Law and Arts University of Southern Queensland in fulfilment of the requirements for the Degree of Doctor of Philosophy.

Kristjanson, P., Neufeldt, H., Gassner, A., Mango, J., Kyazze, F.B., Desta, S. et al. 2012. Are food insecure smallholder households making changes in their farming practices ? Evidence from East Africa. *Food Security* 4: 381–397.

Kuehne, G., Llewellyn, R., Pannell, D., Ouzman, J., Wilkinson, R. and Dolling, P. 2013. *ADOPT: the Adoption and Diffusion Outcome Prediction Tool – smallholder beta version (beta version, June 2013) [Computer software]* Adelaide SA: CSIRO.

Law, A.M. and Kelton, W.D. 2000. *Simulation modeling and analysis*, 3rd edn. New York: McGraw-Hill.

Leonardo, W.J., van de Ven, G.W.J., Udo, H., Kanellopoulos, A., Sitoe, A. and Giller, K.E. 2015. Labour not land constrains agricultural production and food self-sufficiency in maize-based smallholder farming systems in Mozambique. *Food Security* 7: 857–874.

Li, X., Waddington, S.R., Dixon, J., Joshi, A.K. and de Vicente, M.C. 2011. The relative importance of drought and other water related constraints for major food crops in South Asian farming systems. *Food Security* 3(1): 19–33.

Mahoo, H.F., Kahimba, F.C., Mutabazi, K.D., Tumbo, S.D., Rwehumbisa, F.B., Reuben, P. *et al.*, 2012. Adoption and up scaling of water harvesting technologies in Tanzania. In *Water Harvesting Technologies in sub-Saharan Africa*, Chapter 6: State of the Art, eds Christley, W. and Gowing, J. Oxford: Earthscan Publishers.

Makurira, H., Savenije, H.H.G., Uhlenbrook, S., Rockström, J. and Senzanje, A. 2011. The effect of system innovations on water productivity in subsistence rainfed agricultural systems in semi-arid Tanzania. *Agricultural Water Management* 98(11): 1696–1703.

Mourice, S.K., Rweyemamu, C.L., Nyambilila, A.A. and Tumbo, S.D. 2014. Narrowing maize yield gaps under rain-fed conditions in Tanzania: Effects of small nitrogen dose. *Tanzania Journal of Agricultural Sciences* 12(2): 55–65.

Msongaleli, B., Tumbo, S., Rwehumbiza, F. and Kihupi, N. 2015. Determinants of farm-level decisions regarding cereal crops and varieties in semi-arid central Tanzania. *African Journal of Agricultural Research* 10(30): 2968–2978.

Murty, M.V.R., Singh, P., Wani, S.P., Khairwal, I.S. and Srinivas, K. 2007. *Yield gap analysis of sorghum and pearl millet in India using simulation modeling*. Global Theme on Agroecosystems Report No. 37, ICRISAT, Patancheru.

Mutabazi, K.D. 2013. *Scoping study for the Trans-SEC project in Tanzania*. Sokoine University of Agriculture, Tanzania.

Mwinuka, L., Mutabazi, K.D., Graef, F., Maeda, C., Makoko, B. and Swai, E. 2015a. *Agri-food value chains upgrading strategies choices: A participatory smallholder farmer centred approach*. Plant2030 Status Seminar, Berlin, 4–6 March.

Mwinuka, L., Mutabazi, K.D., Makindara, J. and Sieber, S. (2016) Reckoning the risks and rewards of fertiliser micro-dosing in a sub-humid farming system in Tanzania. *African Journal of Science, Technology, Innovation and Development* 8(5–6): 497–508.

Mwinuka, L., Schneider, I., Maeda, C., Mutabazi, K.D., Makindara, J., Graef, F. et al. 2015b. Comparing stakeholder views for mutual acceptable food value chain upgrading strategies in Tanzania. *African Journal of Agricultural Research* 10(12): 1376–1385.

Page, S.L.J., Karanja, D.K., Mbwaga, A.M., Letayo, E.A.S. and Nsemwa, L.T.H. 2010. The underlying cause of the 2009 sorghum failure in Kongwa district and its implications for Tanzania's vulnerability to climate change. *Food Security* 2(2): 157–167.

Pfister, F., Bader, H.P., Scheider, R. and Buccini, P. 2005. Dynamic modeling of resource management for farming systems. *Agricultural Systems* 86: 1–28.

Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P.J. et al. 2007. Global desertification: building a science for dryland development. *Science* 316: 847–851.

Reynolds, T.W., Waddington, S.R., Anderson, C.L., Chew, A., True, Z. and Cullen, A. 2015. Environmental impacts and constraints associated with the production of major food crops in Sub-Saharan Africa and South Asia. *Food Security* 7: 795–822.

Rezende, M.L. and Richardson, J.W. 2015. Economic feasibility of sugar and ethanol production in Brazil under alternative future prices outlook. *Agricultural Systems* 138: 77–87.

Richardson, J.W. 2010. *Simulation for applied risk management*. Unnumbered staff report, Department of Agricultural Economics, Agricultural and Food Policy Center, Texas A&M University, College Station, Texas.

Richardson, J.W., Herbst, B.K., Outlaw, J.L. and Gill II, R.C. 2007. Including risk in economic feasibility analyses: The case of ethanol production in Texas. *Journal of Agribusiness* 25(2): 115–132.

Richardson, J.W., Klose, S.L. and Gray, A.W. 2000. An applied procedure for estimating and simulating multivariate empirical (MVE) probability distribution in farm level risk assessment and policy analysis. *Journal of Agricultural and Applied Economics* 32(2): 229–315.

Richardson, J.W., Schumann, K.D. and Feldman, P.A. 2008. *SIMETAR, simulation & econometrics to analyze risk*. College Station, TX: Texas A&M University, Department of Agricultural Economics, Agricultural and Food Policy Center.

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L. et al., 2009. Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. *Soil and Tillage Research* 103: 23–32.

Sanchez, P.A. 2002. Soil fertility and hunger in Africa. *Science* 295: 2019–2020.

Shiferaw, B., Prasanna, B.M., Hellin, J. and Bänziger, M. 2011. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security* 3: 307–327.

Tabo, R., Bationo, A., DialloMaimouna, K., Kassane, O. and Koala, S. 2005. *Fertiliser microdosing for the prosperity of small scale farmers in the Sahel*. Final report, International Crop Research Institute for the Semiarid Tropics (ICRISAT), Sadore, Niger, 28.

Turinawe, A., Drake, L. and Mugisha, J. 2015. Adoption intensity of soil and water conservation technologies: A case of South Western Uganda. *Environment, Development and Sustainability* 17(4): 711–730.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B. et al., 2010. Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. *Nutrient Cycling in Agroecosystems* 88: 3–15.

Uphoff, N. 2012. Supporting food security in the 21st century through resource-conserving increases in agricultural production. *Agriculture & Food Security* 1: 18.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., and Six, J. 2011. Agronomic use efficiency of N fertiliser in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil* 339: 35–50.

Ville, A.S.S., Hickey, G.M., Locher, U. and Philip, L.E. 2016. Exploring the role of social capital in influencing knowledge flows and innovation in smallholder farming communities in the Caribbean. *Food Security* 8: 535–549.

Vorotnikova, E., Borisova, T. and VanSickle, J.J. 2014. Evaluation of the profitability of a new precision fungicide application system for strawberry production. *Agricultural Systems* 130: 77–88.

Vose, D. 2002. *Risk analysis: a quantitative guide*. New York: John Wiley & Sons.

Wada, Y., van Beek, L.P., van Kempen, C.M., Reckman, J.W., Vasak, S. and Bierkens, M.F. 2010. Global depletion of groundwater resources. *Geophysical Research Letters* 37(20): L20402.