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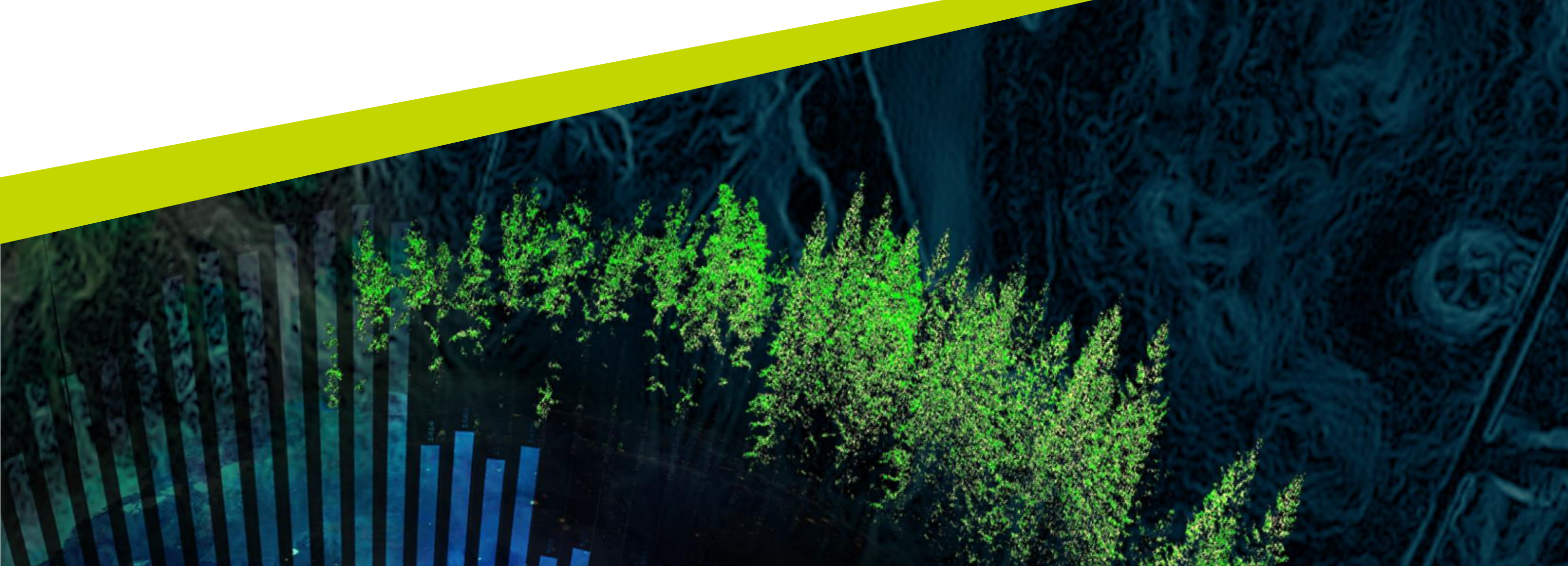

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Abstract

Food insecurity and poverty are of major concern for farmers in Tanzania, and the technologies rainwater harvesting coupled with fertilizer micro-dosing promise to aid in easing these burdens, particularly in a water-limited context. In this study, I performed an ex-post assessment of the impact of these two innovations in the sustainability of households and farms, in two contrasting regions of Tanzania semi-arid Dodoma and semi-humid Morogoro, to see if they would be relevant to promote in the country. The method used accounts for households' and farms' characteristics, estimates sustainability indicators, and uses a difference-in-differences propensity score matching (PSM) estimator. The results indicate contrary to expectations, that the households in the semi-arid region of Dodoma are not benefiting from the adoption of the innovations, neither in food security nor in economic sustainability and even exacerbated the frequency of water conflicts by 7%. On the opposite, in the semi-humid region of Morogoro, these two innovations enhanced households' environmental sustainability and food security by increasing these indices by 3% and 10% respectively. Using aggregated indicators to assess the impact of rainwater harvesting and fertilizer micro-dosing on economic, social and environmental aspects, was relevant to show that these technologies have limited benefits on the sustainability of farmers' households in Tanzania, thus need to be complemented by policies that promote households' characteristics associated with better food security and economic results, such as training for higher levels of education, greater land security, and promoting the cultivation of cash-crops.

Keywords: difference-in-differences, East Africa, food security, innovations, propensity score matching, sustainability indicators, technology adoption, Tanzania

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1. Introduction

1.1. Problem description, research question and objectives

Food insecurity and poverty are a major concern in Tanzania, and farmers are affected by the lack of technologies for agriculture. Tanzania is one of Africa's fastest growing economies with 7% annual GDP growth (The World Bank 2020). Agriculture generates 25% of Tanzania's GDP (World Food Programme 2021) and employs 77% of the working age adults (The World Bank 2020). However, the levels of inequality have increased, and 36% of the people suffered from severe food insecurity in 2017 (Food and Agriculture Organization 2021). The productivity of crops is affected by irregular weather, use of poor technologies and reduction of available labour force (Mmbaga et al. 2002). By 2018, only 10% of Tanzania's cropped area was mechanically cultivated and almost all rain fed (Lana et al. 2018). And although rainfall shortages affect agriculture, in semi-arid areas the most important problems are inter- and intra- seasonal variability; historically, floods have caused 38% of the disasters in Tanzania and droughts 33% of them, often floods and droughts occurred in the same semi-arid area during the same season (Hatibu et al. 2006). Climate change is expected to hinder agricultural activities even more, increasing the frequency and severity of floods and droughts, influencing in the outbreak of pests and disease, putting pressure on crop failure and poor yields (Harvey et al. 2014).

Agricultural innovations in small farms are proposed to face these challenges, however they influence not only labour activities but also the household and the whole socio-economic and ecological context within which they are implemented, therefore sustainability assessments should accompany the process of implementation to evaluate these connections. Environmental themes have generally received more attention in sustainability evaluations (de Olde et al. 2016). But for developing countries genuine sustainability must address food security and income generation immediate needs as well as long-run sustainability (Lee 2005).

The innovations analysed in this study are rainwater harvesting and fertilizer micro-dosing. Rainwater harvesting in situ by tied ridges accumulates the water when there is light rainfall, and in case of heavy rainfall distributes the water and reduces the speed of the water flow within rows (Germer et al. 2021). Fertilizer micro-dosing involves applying small proportions of fertilizer with the seed at the time of planting or as top dressing 3 to 4 weeks after the plant emerges (ICRISAT 2021). Optimized soil moisture and fertilizer have proved to increase crop yields, water use efficiency and nutrients use efficiency (Chilagane et al. 2020) hence they can potentially reduce poverty and improve food security (Habtemariam et al. 2019).

In this study I will account for households-farms characteristics under the Sustainable Livelihoods Approach; evaluate economic, social and environmental sustainability measurements through indicators calculated before and after the adoption of the innovations rainwater harvesting and fertilizer micro-dosing; and determine possible differences between adopters and non-adopters of the innovations by the Difference-in-differences Propensity Score Matching estimator. The question to be answered is: what is the impact of the adoption of rainwater harvesting and fertilizer micro-dosing over the economic, social and environmental aspects of sustainability of households-farms of Dodoma and Morogoro regions of Tanzania?

The specific objectives of this research are: (I) define relevant human, natural, financial, social and physical characteristics of the households-farms in the regions of Morogoro and Dodoma in Tanzania, and their changes, to assess their influence on innovations, (II) estimate the impact of the innovations rainwater harvesting and fertilizer micro-dosing on the overall sustainability of households in the Morogoro and Dodoma regions in Tanzania, (III) estimate the impact of the innovations rainwater harvesting and fertilizer micro-dosing on economic, social and environmental indicators of sustainability in the Morogoro and Dodoma regions in Tanzania, and (IV) estimate the impact of the innovations rainwater harvesting and fertilizer micro-dosing in the food security indicator for Morogoro and Dodoma regions in Tanzania.

1.2. Background

Food insecurity is a global concern and in link with poverty in Sub-Saharan Africa, furthermore, deteriorating environmental conditions are reinforcing this problem, by reducing the quantity and quality of water and soil available for farming and affecting agricultural diversity. The United Nations Zero Hunger Sustainable Development Goal aims to end all forms of hunger and malnutrition by 2030 (United Nations Development Programme 2015). But the population living under extreme poverty condition in Sub-Saharan Africa reached 42.3% by 2019 (World Bank 2020), and 57% of Sub-Saharan Africa's and Southern Asia's population cannot afford a healthy diet (UNICEF 2020). Climate change increased the frequency of extreme weather disasters by three times that of 1970 and 1980 (United Nations Framework Convention on Climate Change 2021), and agriculture has been significantly impacted. Economic losses due to extreme weather disasters that damaged crop and livestock production added up to $30 billion in Africa, for the period 2008 – 2018 (United Nations Framework Convention on Climate Change 2021).

Agricultural research in Africa has oriented towards the production of knowledge and technology to face these difficulties and make agriculture the "motor of sustainable economic growth" (Sumberg 2005). Early economic theory already highlighted the importance of technical and institutional change, for instance List (1841) critics to Adam Smith's poor recognition on the influence of the intellectual abilities on nations' revenues and not only material capital. In the same trend the World Bank's conclusion that investing in knowledge accumulation is decisive rather than physical capital investment, based on the "New Growth Theory" that states increasing marginal productivity of knowledge as an input in production (Romer 1986) (The World Bank 1991). Nevertheless, innovation systems theory recognises the limited benefits that agricultural technology has had for poor people in Sub-Saharan Africa. This is attributed to the instability and site specificity of agriculture and to the failure of the market to allocate technological resources, because poor farmers are in no economic or risk taking position to invest in research and development unless the government or other institutions intervene (Clark 2002).

In this study, the effects of the potentially relevant and easy-to-implement technologies rainwater harvesting and fertilizer micro-dosing adopted in Tanzania are evaluated, this is done by calculating indicators that provide information on the impact of innovations on the three pillars of sustainability in the same analysis. The innovations are now viewed in the frame of a humankind-nature balanced benefitting relationship, rather than just aiming to economic goals related to productivity (Andrade et al. 2020). Some recognized shortcomings of current sustainability studies of agriculture that I target are: not addressing specifically the multi-functionality of agriculture and ignoring some of the three dimensions of sustainability, ecological, economic and social, and not contemplating the interaction and trade-off between sustainability indicators (Bonisoli et al. 2018).

Studying the impact of innovations requires to control for other characteristics of households that may have evolved independently from the adoption of the innovations. The framework applied to account for households' characteristics is the Sustainable Livelihoods Approach that is adequate for developing countries where there is no clear separation between household and farms characteristics. The Sustainable Livelihoods approach considers that people are operating under a vulnerability situation therefore it states that they manage assets considered poverty reduction factors (DFID 1999), and classifies the capital into five categories: financial, physical, natural, human and social (Quandt 2018).

This study uses the Difference-in-differences Propensity Score Matching method to evaluate the influence of self-selection to adopt the innovations, and analyse if the characteristics of the individuals adopting the innovations are responsible for their results on sustainability or if they are influenced by the treatment. The Difference-in-differences Propensity Score Matching approach is effective in reducing the time varying bias and selection bias that could arise in before-and-after comparison (Udagawa et al. 2014). There is a limited literature of the application of this method to analyse agricultural innovations' impact on sustainability of farmers in developing countries; while it is known that the adoption of sustainable agriculture varies depending on farmers' socio-economic characteristics, attitude and beliefs (Comer et al. 1999).

1.3. Literature review

A basis for this research is the Sustainable Livelihoods Approach, which is the framework used for reporting the households' and farms' characteristics which will be controlled for changes during the period of study and for their connection with the adoption of the innovations. There is some literature using the sustainable livelihood strategy framework to evaluate the connection between economic and social choices of households such as productive activities and assets investments, and their impact on ecological, social and economic results (Rakodi 1999; Barrett et al. 2001; Pender et al. 2001; Jansen et al. 2006b). Particularly, Jansen et al. (2006) made a qualitative and quantitative measurement of livelihood strategies based on land and labour use in Honduras hillside, with the objective of providing information about potential policies for conservation of the natural resources. The authors used factor and cluster analysis to cluster farm households based on their land resources and labour use, and through regression models they analysed the relationship of livelihood strategies, physical, financial and social capital, with income per capita, land management and soil conservation practices at parcel level. The results indicate that security in land tenure and education promote sustainable land-use practices and income, and that investments to facilitate households-farms' extension of productive assets should focus on farms that have off-farm employment because of their higher opportunity costs of labour. The study of Jansen et. al provides a reference on how the sustainable livelihood approach captures household-farms' characteristics, endowments and priorities, so then they can be connected them to the farms' outcomes, to assess the effectiveness of support for adoption of valuable practices. Nevertheless, it is recognized that the Sustainable Livelihoods Approach needs to be adequately coupled to other analysis to capture the impact of agricultural systems, in our case to evaluate the impact of technologies on the social, economic and environmental sustainability, given adopters characteristics.

For impact assessments of rainwater harvesting and fertilizer micro-dosing, most studies focus on ecological effects or results on yields (Binder et al. 2010), at the landscape and field level, while the multiple impacts of these technologies on the sustainability of households is limited. For instance, Saidia et al. (2019) conducted field experiments to assess the impacts in yields and land utilization efficiency of tied ridges water harvesting, fertilizer micro-dosing and intercropping, the experiment was performed in sub-humid regions of Tanzania. The authors concluded that combining inter-cropping with water harvesting and fertilizer micro-dosing can increase the income and food security of small-hold farms in sub-humid Tanzania. On the other hand, Vohland & Barry (2009) made an evaluation of food security, income generation, and the ecological impact concentrating on the landscape scale, because they aimed to evaluate water dynamics beyond field level in African drylands. The approach applied was the recompilation of literature about rainwater harvesting, and they also performed a nonlinear regression relating grain harvest against mean precipitation. The authors concluded that the effect of rainwater harvesting on landscape functions is positive respect to aquifers recharge and soil water, while the results for the social and economic sustainability will highly depend on the involvement of farmers and general communities. Vohland & Barry suggested that a more complete quantitative analysis at the household level is required, to measure socioeconomic factors. Studying the impacts of rainwater harvesting and fertilizer micro-dosing at the household level, connecting the economic, social and environmental sustainability, would result on a more comprehensive evaluation of these technologies for further recommendations about their use.

Studies to assess the economic, social and environmental impacts of rainwater harvesting and fertilizer micro-dosing in Tanzania have focused on expected results, while to the best of my knowledge no ex-post assessment that includes the three dimensions has been made. Schindler et al. (2016a) combine stakeholders' and researchers' knowledge in an ex-ante (before) impact assessment of agricultural innovations that include rainwater harvesting and fertilizer micro-dosing. After applying the impact assessment approaches *Framework for participatory impact assessment* and *ScaIA-Food Security* to consider stakeholders and researchers evaluations, Schindler et al. conclude that farmers consider indirect impacts not observed by researchers, that are important to improve the assessments. Some differences include farmers' consideration of the risk of lack of rain and chemical fertilizer application, that would increase yield failure in case of drought even further, instead of generating the yield increases expected by researchers. Moreover, farmers envision the increased workload to construct the infiltration pits that would reduce the field sizes that they are able to cultivate due to limited labour availability. On the other hand, Graef et al. (2017) focus on an expert-based ex-ante social, economic and environmental impact assessment of a group of innovations that include also rainwater harvesting and fertilizer micro-dosing. The authors highlighted that rainwater harvesting and fertilizer micro-dosing are expected to have a higher impact in the semi-arid region by improving food diversity, social relations and working conditions. The ex-ante assessments mentioned provide expected results of functioning and impact of innovations that will be confirmed or not in this study.

Regarding the method applied in this research, Difference-in-differences combined with Propensity Score Matching has been used to analyse the impact of the implementation of agricultural policies and of the adoption of agricultural technologies, given panel data and non-random treatment assignment, however as far as I know it has not been coupled with sustainability indexes before. An approximation to the use of these methods in the present research is the study of Dillon (2011), who examined the impact of small-scale irrigation adoption over households' consumption, assets and the informal insurance practice of food sharing between irrigators and non-irrigators, the research is done for northern Mali. The author used Difference-in-differences Propensity Score Matching considering that access to irrigation is not random but influenced by households' characteristics such as family size, education of the household head, assets, landholdings, and ethnicity. The conclusion reached by the author is that small-scale irrigation projects have the direct impact of benefitting households' consumption by 27 to 30% respect rainfed and water-recession cultivation in regions affected by risk of droughts, but also the indirect impact of promoting what is called informal social insurance that consists of the increase of savings and sharing within the villages. Läpple & Thorne (2019) used an extension to the method by applying a Generalised Propensity Score to assess the effect of different levels of innovativeness of Irish dairy farmers on their economic sustainability. The authors concluded that innovativeness in general generates higher economic gains, but not in a linear way, and that highly innovative farmers can still improve their economic results from further innovativeness. These studies show examples of the use of the method and what we could expect in food security from the application of water access technologies, and economic gains from innovations adoption, but also support the need of doing a context-based analysis that considers regional and farmers' characteristics when assessing the impact of agricultural technologies, and coupling the method with composite indicators appears adequate to evaluate effects in sustainability.

The literature shows that the Sustainable Livelihoods framework and Difference-in-differences Propensity Score Matching may be complementary approaches to identify characteristics of farms and households, and assess their connection to the effects of agricultural innovations on sustainability. To the date, an ex-post assessment of the impact of rainwater harvesting and fertilizer micro-dosing in the economic, social and environmental aspects of sustainability of farmers' households in Tanzania has not been done.

2. Materials and methods

The data used was collected by a survey conducted in Tanzania as part of a large trans- and inter disciplinary research project[1]. The dataset was organized in a panel with observations per household and consisted of 448 observations for the region of Dodoma and 444 for the region of Morogoro in the year 2013, and 420 observations for Dodoma and 391 for Morogoro in the year 2016.

Rainwater harvesting and fertilizer micro-dosing were assessed in this study due to the higher adoption rate and importance that farmers attributed to these technologies in their food production process, respect to other innovations, as assessed by Schindler et al. (Schindler et al. 2016b).

2.1. The methods

The process followed in this research to assess the impact of the innovations rainwater harvesting and fertilizer micro-dosing on farms-households sustainability consisted on three main steps: (1) definition of the household characteristics according to the Sustainable Livelihoods Approach, (2) calculation of the sustainability indicators and composite sustainability index, and (3) estimation of the impact on sustainability by Difference-in-differences Propensity Score Matching.

2.1.1. Household characteristics with Sustainable Livelihoods Approach

Data from a survey for the years 2013 and 2016 was used to classify the information, calculate ratios, and transform into dummy variables, to present the household characteristics according to the Sustainable Livelihoods framework. The Sustainable Livelihoods Approach classifies assets considered as poverty reduction factors, into five categories of capital: financial, physical, natural, human and social (Quandt 2018).

[1] The Trans-SEC project proposes agricultural innovations as a way to use research and knowledge to face the need for food security of the rural poor population in Tanzania. For more information see: http://www.trans-sec.org/

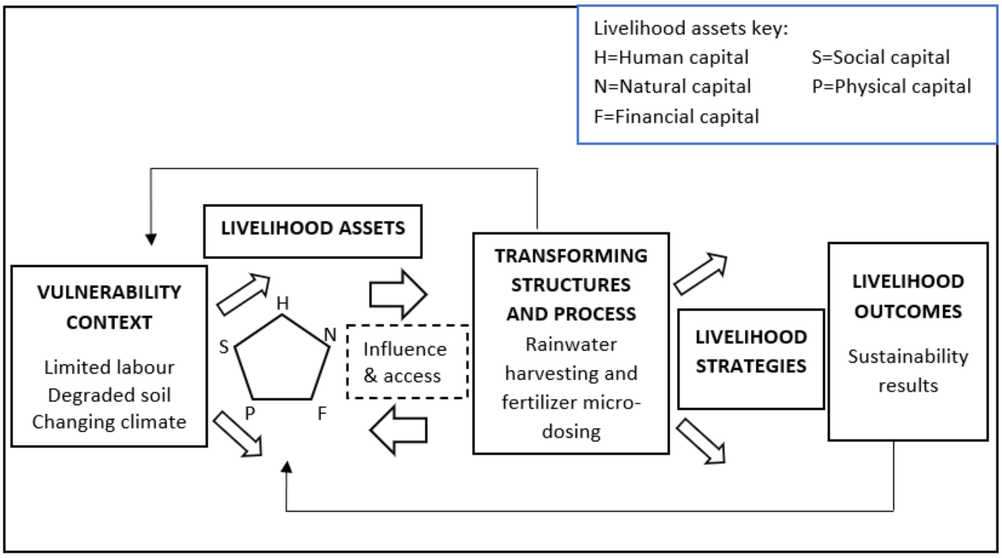

Figure 1: The Sustainable Livelihoods Framework scheme. Based on the figure presented by the Department for International Development (DFID) (1999)

2.1.2. Calculation of sustainability indicators and composite indices

The sustainability indicators were chosen based on literature about researchers' and farmers' opinion of aspects that represent sustainability, they pertain the economic, social and environmental pillars of sustainability and use the information available from the surveys. Thus, I adopted an approach similar to the one by Yegbemey et al. (2014), who used a participatory method to account for farmers' and agricultural extension officers' viewpoints when selecting the indicators to evaluate agricultural sustainability. Also, the selection of the indicators in each component of the sustainability pillars was done following the process proposed by ul Haq & Boz (2018) to account for site specific features. Table 1 presents a list of the indicators calculated and includes information about the direction which explains if the indicator is considered to influence positively in the sustainability component ("Additive") or negatively ("Subtractive").

Table 1: Description of sustainability indicators

Pillar	Component	Indicator	Units	Direction
Environmental	Soil management	Quantity of applied fertilizer	Kg / ha	Additive
		Quantity of animal manure applied	Kg / ha	Additive
		Crop area perceived as unfertile	% area	Subtractive
		Crop area with perceived decrease in fertility	% area	Subtractive
		Crop area under legume	% area	Additive
		Crop area with residues left on the field	% area	Additive
		Area where there is an intent to invest in soil fertility	% area	Additive
		Average tree density	Number of trees / ha	Additive
		Area under erosion control measures	% area	Additive
	Water management	Presence of irrigation	Yes – No	Subtractive
		Rainfall water use efficiency	Kg / ha / mm of rainfall	Additive
		Change in household water consumption	Litres/day	Subtractive
		Water harvesting	Yes – No	Additive
		Water use conflict	% of amount	Subtractive
	Agricultural diversity	Tree diversity	Number of species	Additive
		Crop diversity	Number of species	Additive
		Livestock diversity	Number of species	Additive
Economic	Crop profitability	Crop gross margin	USD / ha	Additive
		Crop expenditures	USD / ha	Subtractive
		Labour productivity	USD / person	Additive
		Post-harvest loss	% amount	Subtractive
	Profitability	Net household income	USD	Additive
	Stability	High income fluctuation	Yes – No	Subtractive
		Has savings	Yes – No	Additive
	Reduction of vulnerability to shocks	Loss of income due to shock	USD	Subtractive
		High severity of shock	Yes – No	Subtractive
		Time to recover after shock	Number of months	Subtractive

Social	Food security	Potential Food Availability index (PFAI)[2]	Ratio	Additive
		Months of inadequate food provisioning	Number of months	Subtractive
		Food Consumption Score (FCS)[3]	Score	Additive
		Coping Strategies Index (CSI)[4]	Score	Subtractive
	Health	Health insurance binary	Yes – No	Additive
		Healthy household members	% of people	Additive
	Wellbeing	Hours worked	Hours/active household member	Subtractive
		Perceived deterioration of household situation	Yes – No	Subtractive
		High impact of income fluctuations on wellbeing	Yes – No	Subtractive
	Social capital	Information network	Number of sources	Additive
		% of crops receiving support from farmers group	%	Additive
	Land security	Land title ownership	% of area	Additive
		Secure land	% of area	Additive
		Land use conflict	% of area	Subtractive

Using these sustainability indicators, composite indices were calculated for each region, Dodoma and Morogoro. Before this calculation continuous variables were treated for missing values, by completing the information using the function imputePCA from the missMDA package on R, which predicts the missing values through a model based on complete observations. The number of values missing from the dataset of indicators of year 2013 were 95 out of 41,924, and for the dataset of year 2016 were 12 out of 34,062. Outliers were caped to control for data recording errors, by replacing the values above the 95th percentile by the 95th percentile, and values below the 5th percentile by the 5th percentile. Next, the

[2] Potential Food Availability index (PFAI): represents a households' potential food consumption expressed in energy equivalents respect its energy needs for a year (Frelat et al. 2016).
[3] Food Consumption Score (FCS): the possible range is between 0 and 112 points and represents the frequency weighted diet diversity (World Food Programme 2015).
[4] Coping Strategies Index (CSI): represents the frequency and severity of coping behaviours that households adopt when they do not have access to enough food, a lower score indicates less food insecure (Caldwell & Maxwell 2008).

calculation of the composite indices consisted of the normalization of the component indicators, assignment of weights, and aggregation of the component indicators.

The normalization of the component indicators was done to obtain homogenous units that enables their comparability and performing arithmetic operations with them. The method used for normalizing was the min-max normalization (see Gómez-Limón & Sanchez-Fernandez 2010; Haileslassie et al. 2016; Mutyasira et al. 2018), considering the minimum and maximum of the whole data of both periods 2013 and 2016. Equation (1), for additive indicators, and equation (2), for substrative indicators, present the formula used for normalizing.

$$xnorm = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (1)$$

$$xnorm = \frac{\max(x) - x}{\max(x) - \min(x)} \quad (2)$$

Where *xnorm* is the normalized value of the observation *x*, and *min(x)* and *max(x)* are the minimum and maximum observations in the whole 2 years' sample. The resulting value will lie between [0, 1], being 0 the least sustainable and 1 the most sustainable. Then, the normalized indicators were assigned weights which summed up to 1 per component. Binary indicators were given half the weight of continuous indicators, following Chopin et al. (2019) who explain that binary indicators provide less information. Lastly, the composite indices per component were calculated by aggregating the weighted indicators. The formula applied was the weighted sum:

$$CI = \sum_{i=1}^{n} w_i * xnorm_i \quad (3)$$

Where *CI* stands for composite index, *n* is the number of indicators for the composite index, *w* is the weight assigned to the component indicator, and *xnorm* is the normalized indicator. Following, composite indices per pillar of sustainability and a composite index of sustainability, composed by indicators for the three pillars, were calculated by a weighted sum where each component had the same weight considering that they had equal importance.

2.1.3. Estimation of the impact on sustainability by Difference-in-differences Propensity Score Matching

The method to evaluate the impact of the adoption of the innovations on the sustainability of households-farms was Differences-in-differences combined with Propensity Score Matching, which are commonly applied to analyse the impact of policies and programmes. Differences-in-differences evaluates the impact of a treatment on the outcome change over a period by comparing the treated individuals with the matched control non treated ones. Propensity Score Matching controls for selection bias, i.e. making the two groups comparable. As defined by Caliendo & Kopeinig (2008), selection bias occurs when we want to assess the difference in the outcome of the individuals with and without the treatment, but we cannot observe both outcomes for the same observation at the same time, either the individual was treated or not. Comparing treated and non-treated units might result in biased estimates and this happens when there exist characteristics that affect simultaneously the outcome and the probability to receive the treatment (Chabé-Ferret 2015). If that happens, the difference in the outcome may be due to the difference in the characteristics between the individuals and not in the treatment itself. This issue often arises in non experimental setting. Therefore, using Differences-in-difference with Propensity Score Matching looks adequate for this study, given the impact analysis we are aiming to perform and considering that the adoption of the innovations was decided by each farmer, that may be prompt to self-select given their personal and labour conditions.

I followed the procedure applied by Arata & Sckokai (2016) for the Difference-in-differences Propensity Score Matching method. First the Propensity Score Matching was performed, as portrayed in figure 2.

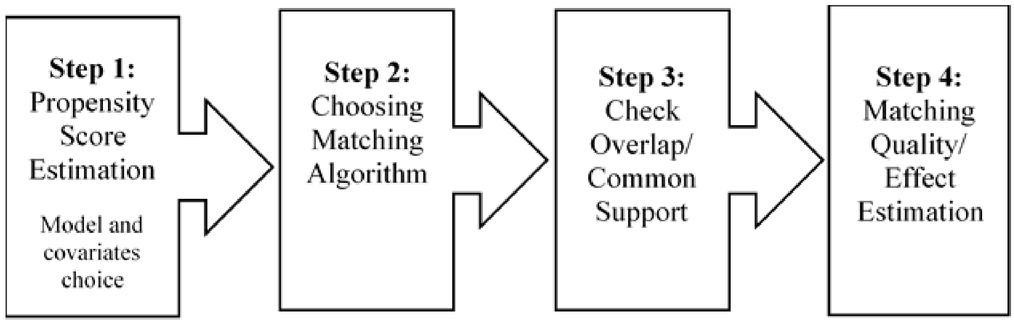

Figure 2: Propensity Score Matching implementation steps. Representation inspired by the Propensity Score Matching steps presented in the paper of Caliendo & Kopeinig (2008)

To overcome the selection bias, the Propensity Score Matching matches each treated individual with one or more non-treated individuals that have similar observed characteristics called covariates, *X*. According to Rosenbaum & Rubin (1983), the probability of being treated *P(X)* is conditioned on a function of *X*, and the matching is based on *P(X)*. The covariates were chosen using a logistic regression and followed Caliendo & Kopeinig (2008) instruction that outcome variables must be independent on the treatment and conditional on the propensity score. The *average treatment effect on the treated (ATT)* is used to evaluate the effect of the adoption of the innovations and is calculated as the difference in the mean outcomes of the treated units and the matched control group.

$$ATT = \{E\left(Y^1 \middle| D = 1, P(X)\right) - E\left(Y^0 \middle| D = 0, P(X)\right)\} \quad (4)$$

Where Y^1 and Y^0 are the outcomes for a household in the case of treatment and no treatment, respectively. D is a dummy variable, indicating that the individual was treated when it takes the value of 1.

Next, the satisfaction of the conditional mean independence assumption and the common support condition was verified. As stated by Rosenbaum & Rubin (1983), the conditional mean independence assumption indicates that after conditioning on the propensity score, the mean outcomes must be independent from the treatment state. The common support condition assures that for each treated individual a potential matched non-treated individual is found, by considering only those participants whose probability of being treated is lower than 1. Matching can be done using different matching algorithms that give different weights to the control units, as described by Caliendo & Kopeinig (2008), the algorithm chosen in this study was nearest neighbour matching with replacement, with 10 neighbours and caliper of 0.1, that balanced the trade-off between bias and variance.

After the Propensity Score Matching method controlled for the selection bias on observables, the Differences-in-differences method was applied to compare the change in the outcomes of the treated and non-treated for the period of study. The combination of the Propensity Score Matching with the Differences-in-differences estimator removes the bias caused by common time trends that are not related to the treatment, as well as partially overcomes the possibility of selection bias due to unobserved variables (Heckman et al. 1997). The Differences-in-differences method compared the observations that were matched using the propensity score, and was calculated by the equation (5).

$$DID = \frac{1}{N}\sum_{i=1}^{I\cap S}[(Y_{it}^{1} - Y_{it'}^{0}\big|D = 1) - \sum_{j=1}^{J\cap S} w_{ij}(Y_{jt-}^{0}Y_{jt'}^{0}|D = 0)] \quad (5)$$

Where *N* is the number of individuals in the treated group who are in the region of common support *S*, *i* identifies the treated unit (here the household), *j* identifies the non-treated unit, *t* states for the post-treatment period, *t'* states for the pre-treatment period, w_{ij} indicates the weights that range between [0, 1], and depend on the distance between the probability of treatment P_i and P_j.

Therefore, the *average treatment effect on the treated*, when combining Propensity Score Matching with Difference-in-differences, indicated the difference in the mean growth of the outcome between the group of treated and non-treated.

$$ATT = \{E\big(Y_t^1 - Y_{t'}^0\big|D = 1, P(X)\big) - E\big(Y_t^0 - Y_{t'}^0\big|D = 0, P(X)\big)\} \quad (6)$$

2.2. The dataset descriptive statistics

The study of the innovations' impact was performed in two regions of Tanzania, Morogoro and Dodoma because of their contrasting environmental and socio-economic conditions that stand out when the regions are compared, and because both regions represent a majority (between 70 and 80%) of the farming systems found in the country (Graef et al. 2014). Table 2 presents a comparison of their characteristics.

Table 2: Summary of Morogoro and Dodoma regions environmental and agricultural characteristics (Sources: Mnenwa et al. 2010; Graef et al. 2014; World Bank 2020)

Characteristics	Morogoro	Dodoma
Biophysical	Climate: semi-humid	Climate: semi-arid
	Precipitation: 600–800 mm annual	Precipitation: 350–500 mm annual
	Temperature: average 25^0C annual. Varies between 18^0C to 30^0C in the lowlands	Temperature: average 22^0C annual. Varies between 14^0C to 30^0C
	Topography: diverse. Flat plains, highlands, and dry alluvial valleys	Topography: almost homogeneous. Flat plains and small hills
Socio-economic	Agriculture engages around 70 percent of the region's labour force	Agriculture engages around 70 percent of the region's labour force
	Different levels of sensibility regarding food security	Predominance of high food insecurity
Agricultural	Major food crops: maize, rice, sorghum, legumes, horticulture	Major food crops: sorghum, millet, maize
	Major cash crops: sesame, sunflower, sugarcane, cotton, sisal	Major cash crops: sesame, groundnuts, sunflower
	Livestock: poultry, cattle, goats. Secondary source of income	Livestock: poultry, cattle, sheep, goats. Main source of income

2.2.1. Household characteristics

In Dodoma, on average the family size is 5 people and the household head is 50 years old (Table 3). The mean experience in agriculture is 20 years and the average education is four years. The number of hectares managed by each household are around 2.5, and in the year 2016, a mean of 80% of was used for cropping. On average all active members work on-farm, while 40% worked off-farm on the year 2016. The hours worked per hectare increased from year 2013 to year 2016, reaching about 650. The area perceived as fertile doubled for the same period from

30 to 60%. While the percentage of farms affected by drought decreased in 20%. The percentage of households that cultivate cash crops in Dodoma doubled to reach 20% in the year 2016. In the same way, the cultivation of maize doubled in similar values. The expenditure on fertilizers and pesticides more than doubled between 2013 and 2016 in Dodoma, to reach 8.3 USD per hectare. The household income perceived from crops increased from 30 to 40%. While the value of the food expenditures increased to almost 994 USD in the year 2016. The value of productive assets owned by the households is on average 75 USD.

The average family size in Morogoro is between 4 and 5 persons and the household head is 50 years old, like Dodoma (Table 4). The average years of experience in agriculture in Morogoro are less than in Dodoma, though they increased respect the year 2013 to reach 16 years. The years of education are 4. Morogoro households manage 2.5 hectares of land from which 80% is cropped area, same as in Dodoma. The share of cropped area dedicated to cash crops kept constant in Morogoro, while the share dedicated to maize decreased to 40% in the year 2016. The labour hours invested per hectare increased to 700 hours in the year 2016. Similar to Dodoma, in Morogoro on average all active household members work on-farm while the percentage working off-farm increased to 30%, still lower than in Dodoma. The share of area perceived as fertile increased to 60%, same level as Dodoma, though in Morogoro the percentage for year 2013 was higher (50%). On the other hand, the households affected by drought in Morogoro also increased. The value of fertilizers and pesticides expenditures per hectare in Morogoro was around 12 USD per hectare, for the years 2013 and 2016, higher than in Dodoma. The percentage of household income from cropping decreased from 60% to 50% in the year 2016, contrary to Dodoma where it increased. The value of food expenditures was around 1055 USD in the year 2016. The value of productive assets doubled from the year 2013 to the year 2016, reaching almost 64 USD.

Table 3: Summary statistics of main household characteristics of Dodoma

Variable	Unit	Dodoma 2013					Dodoma 2016					**Difference**
		n	**mean**	Sd	Min	max	n	**mean**	sd	min	max	**2016 - 2013**
Family size	Number people	448	**5**	2.2	1	18	420	**5**	2.2	1	12	**0.2**
Age of household head	Years	447	**49**	16.9	22	110	420	**51**	16.9	22	100	**2.2**
Female household head	Yes-No	448	**0.2**	0.4	0	1	420	**0.2**	0.4	0	1	**0**
Experience in agriculture	Years	448	**20**	17.2	0.8	84	420	**20**	13.6	1	77	**0.2**
Education of household head	Years	424	**4**	3.4	0	16	415	**4**	3.5	0	14	**0.2**
Total labour invested per land unit	hours/ha	448	**562**	748.4	16.4	9452	420	**651**	508.8	73.3	5647.1	**88.9**
Share of hired labour in total labour	%	448	**0.1**	0.1	0	1	420	**0.1**	0.2	0	0.9	**0**
Active members on-farm	%	375	**1**	0.1	0.2	1	406	**1**	0.1	0.2	1	**0**
Active members off-farm	%	446	**0.4**	0.4	0	1	420	**0.3**	0.4	0	1	**-0.1**
Total area managed by the household	Ha	448	**2.4**	2.4	0.2	32.1	420	**2.5**	3.6	0.2	61.3	**0.1**
Share of total area perceived by the household as fertile	%	448	**0.3**	0.4	0	1	420	**0.6**	0.4	0	1	**0.3**
Affected by drought	Yes-No	448	**0.7**	0.5	0	1	420	**0.5**	0.5	0	1	**-0.2**
Share of total area used for cropping	%	448	**0.9**	0.2	0	1	420	**0.8**	0.2	0	1	**-0.1**
Share of cropped area dedicated to cash crops	%	448	**0.1**	0.2	0	1	420	**0.2**	0.2	0	0.8	**0.1**
Share of cropped area dedicated to maize	%	448	**0.1**	0.1	0	0.8	420	**0.2**	0.2	0	1	**0.1**
Cropped area irrigated	Yes-No	448	**0**	0	0	0.3	420	**0**	0	0	0.4	**0**
Value of fertilizer and pesticide expenditures	USD/ha	448	**2.8**	11	0	125.8	420	**8.3**	44.2	0	822.9	**5.5**
Share of household income generated by crop production	%	448	**0.3**	0.3	0	1	420	**0.4**	0.3	0	1.2	**0.1**
Value of food expenditures	USD	448	**855**	702.6	0	4288.4	420	**993**	1153.6	0.3	18421.2	**138.5**
Value of productive assets	USD	448	**73**	161.6	0	2358.3	420	**75**	276.2	0	4879.3	**2.8**

Table 4: Summary statistics of main household characteristics of Morogoro

Variable	Unit	Morogoro 2013					Morogoro 2016					**Difference 2016-2013**
		n	**Mean**	Sd	min	max	n	**mean**	sd	min	max	
Family size	Number people	444	**4.4**	2.3	1	13	391	**5**	2.4	1	19	**0.6**
Age of household head	Years	443	**47**	17	19	116	391	**50**	16	22	100	**2.9**
Female household head	Yes-No	444	**0.2**	0.4	0	1	391	**0.2**	0.4	0	1	**0**
Experience in agriculture	Years	444	**13**	11.8	1	82	391	**16**	12.4	2	87	**3.5**
Education of household head	Years	440	**4**	3.3	0	14	390	**4**	3.3	0	17	**-0.1**
Total labour invested per land unit	hours/ha	444	**653**	737	21	9866.7	389	**699**	553.1	0	3632.4	**46.7**
Share of hired labour in total labour	%	444	**0.2**	0.3	0	1	390	**0.2**	0.3	0	1	**0**
Active members on-farm	%	392	**1**	0.1	0.2	1	376	**1**	0.1	0.3	1	**0**
Active members off-farm	%	442	**0.2**	0.4	0	1	391	**0.3**	0.4	0	1	**0.1**
Total area managed by the household	Ha	444	**2.1**	1.9	0.1	24.3	391	**2.5**	5.1	0.1	93.1	**0.4**
Share of total area perceived by the household as fertile	%	444	**0.5**	0.5	0	1	391	**0.6**	0.4	0	1	**0.1**
Affected by drought	Yes-No	444	**0.1**	0.3	0	1	391	**0.3**	0.5	0	1	**0.2**
Share of total area used for cropping	%	444	**0.8**	0.2	0	1	391	**0.8**	0.3	0	1	**0**
Share of cropped area dedicated to cash crops	%	444	**0.2**	0.3	0	1	391	**0.2**	0.2	0	0.9	**0**
Share of cropped area dedicated to maize	%	444	**0.6**	0.3	0	1	391	**0.4**	0.3	0	1	**-0.2**
Cropped area irrigated	Yes-No	444	**0**	0.1	0	1	391	**0**	0.1	0	1	**0**
Value of fertilizer and pesticide expenditures	USD/ha	444	**12.5**	77.9	0	1028.4	391	**12.1**	31.2	0	330.7	**-0.4**
Share of household income generated by crop production	%	444	**0.6**	0.3	0	1	391	**0.5**	0.4	0	1	**-0.1**
Value of food expenditures	USD	444	**968**	926.4	0	7676.8	390	**1054**	766.7	0	4298.3	**85.7**
Value of productive assets	USD	444	**29**	63.1	0	603.2	391	**63**	331.9	0	6197.1	**33.8**

2.2.2. Sustainability indicators

Disaggregated results about the sustainability indicators' components in Appendix 1, tables 13 and 14. In the table 5 information about the composite indices for Dodoma for the years 2013 and 2016 is presented, and the difference between the years has been calculated.

Table 5: Summary statistics of composite indices for Dodoma

	Dodoma 2013 (n = 448)		Dodoma 2016 (n = 420)		Difference 2016 – 2013
	Mean	Sd	mean	sd	
Soil management	0.36	0.12	0.33	0.11	-0.03***
Water management	0.54	0.12	0.56	0.11	0.02***
Agricultural diversity	0.24	0.14	0.24	0.12	0
Crop performance	0.55	0.09	0.55	0.09	0
Profitability	0.22	0.25	0.28	0.25	0.06***
Stability	0.35	0.34	0.65	0.35	0.3***
Vulnerability reduction	0.7	0.19	0.75	0.15	0.05***
Food security	0.43	0.15	0.54	0.15	0.11***
Health	0.66	0.21	0.65	0.23	-0.01
Wellbeing	0.62	0.24	0.64	0.23	0.02
Social capital	0.24	0.24	0.13	0.13	-0.11***
Land security	0.48	0.19	0.5	0.2	0.02
Environmental index	0.38	0.08	0.38	0.07	0
Economic index	0.46	0.12	0.56	0.13	0.1***
Social index	0.49	0.1	0.49	0.1	0
Overall index	0.44	0.07	0.48	0.08	0.04***

*Note: *p<0.1; **p<0.05; ***p<0.01*

The overall sustainability index for Dodoma that includes the social, economic and environmental indicators, increased significantly, possibly related to the rise in the economic index. There is a significant increase in the economic index and in its component indicators for profitability, stability, and reduction of vulnerability. Crop performance had no significant change. The composite environmental index had no significant change between years, however the indicator for soil management decreased, while the indicator for water management increased. The composite social index for Dodoma had no significant change. However, the indicator for food security increased significantly and the indicator for social capital decreased significantly.

For Morogoro, the sustainability composite indices for the years 2013 and 2016 and the comparison between years is presented in the table 6.

Table 6: Summary statistics of composite indices for Morogoro

	Morogoro 2013 (n = 444)		Morogoro 2016 (n = 391)		Difference 2016 – 2013
	Mean	Sd	mean	Sd	
Soil management	0.3	0.09	0.32	0.1	0.02***
Water management	0.54	0.09	0.54	0.11	0
Agricultural diversity	0.17	0.11	0.25	0.11	0.08***
Crop performance	0.63	0.13	0.54	0.12	-0.09***
Profitability	0.29	0.29	0.32	0.28	0.03
Stability	0.55	0.33	0.57	0.34	0.02
Vulnerability reduction	0.85	0.19	0.73	0.17	-0.12***
Food security	0.53	0.17	0.58	0.14	0.05***
Health	0.63	0.2	0.63	0.23	0
Wellbeing	0.77	0.2	0.6	0.24	-0.17***
Social capital	0.12	0.15	0.1	0.13	-0.02**
Land security	0.39	0.18	0.43	0.2	0.04***
Environmental index	0.34	0.06	0.37	0.07	0.03***
Economic index	0.58	0.15	0.54	0.14	-0.04***
Social index	0.49	0.08	0.47	0.1	-0.02***
Overall index	0.47	0.07	0.46	0.08	-0.01*

*Note: *p<0.1; **p<0.05; ***p<0.01*

The overall sustainability index, that includes the economic, social and environmental pillars, reduced in Morogoro between 2013 and 2016. The composite index for environmental sustainability significantly increased. In contrast to the results for Dodoma, in Morogoro there was a significant increase in the soil indicator and no change in the water indicator, while the diversity indicator increased significantly between years. The index for the economic sustainability had a significant decrease. Respect the indicators that compose it, crop performance and vulnerability reduction decreased significantly. The composite index for social sustainability had a significant decrease. There was a significant increase in food security and land security, but a significant decrease in wellbeing and social capital.

3. Results

3.1. Characteristics associated with the adoption of the innovations

Before presenting the final results of the Difference-in-differences Propensity Score Matching method, I present information regarding the covariates used for balancing in the Propensity Score Matching and the balance achieved. The logit model, as well as the whole consequent propensity score matching analysis, was carried out separately for Dodoma and Morogoro due to the differences between their biophysical characteristics. I chose the covariates expected to influence on the adoption of the innovations based on their statistical significance and relevance for the adoption of the treatment according to literature and experts' opinion. In the table 7, I present the logistic regressions. For Morogoro 9 variables were chosen from which 3 are statistically significant, while for Dodoma 7 variables were chosen from which 2 are statistically significant.

Regarding the balance of the sample, the evaluation through t-tests demonstrated that only few covariates show a statistically significant difference in the mean before the matching between the treated and the control group, evaluated at the 10% level of significance (see Appendix 1 tables 15,16,17,18). In Dodoma, the control group tended to have a bigger share of cash crops than the treated group. For Morogoro, adopters tended to have more years of education and a higher land security indicator than non-adopters. After applying the matching algorithm all the covariates were balanced for both regions (see Appendix 1 figures 3 and 6). The variation in results before and after matching shows the usefulness of matching to reach unbiased results (see unmatched sample results in the Appendix 1 table 19 and 20).

Table 7: Estimates of the logistic regression for Morogoro and Dodoma

	Dependent variable:			
	Treatment Morogoro	sd	Treatment Dodoma	sd
Age of household head	0.011	(0.01)	-0.004	(0.01)
Education of household head	0.100**	(0.05)	-0.003	(0.04)
Hired labour	-1.142*	(0.61)		
Total area managed by the household	0.090	(0.06)	0.050	(0.05)
Share of total area used for cropping	0.543	(0.72)	0.800	(0.52)
Share of cropped area dedicated to cash crops	-0.991	(0.71)	-1.328*	(0.76)
Share of cropped area dedicated to maize	-0.780	(0.63)		
Total labour invested per land unit	-0.00002	(0.00)	-0.00001	(0.00)
Land security index	1.479*	(0.75)		
Value of productive assets			0.001*	(0.00)
Constant	-2.964***	(1.04)	-1.591**	(0.64)
Observations	388		420	
Log Likelihood	-173.64		-236.72	
Akaike Inf. Crit.	367.28		489.45	

*Note: *p<0.1; **p<0.05; ***p<0.01*

The tested balancing property in the covariates allow to use the Difference-in-differences Propensity Score Matching as an approach to ensure the treated and the matched control group are comparable and no self-selection biases the outcome results. The table 8 shows the number of households considered in the Difference-in-difference regression (sample size after applying the matching algorithm).

Table 8: Balanced sample sizes

Number of households	Dodoma	Morogoro
Treated group		
Before matching	110	69
After matching	107	64
Control group		
Before matching	310	319
After matching	290	259
Matching algorithm	10:1 nearest neighbour matching with replacement and caliper of 0.1	

3.2. Few impacts of the innovations in Morogoro and no influence in Dodoma

The estimated impact of adopting rainwater harvesting and fertilizer micro-dosing over the economic, social and environmental aspects of sustainability of households-farms of Dodoma and Morogoro regions of Tanzania are presented in tables 9 and 10. For Morogoro though the composite sustainability was not impacted by the adoption of the innovations, environmental sustainability and food security improved, while there was no major effect on the economic and social sustainability. In Dodoma, the composite sustainability index was not significantly impacted by the adoption of the innovations, and neither the indicators for each of the economic, social and environmental pillars of sustainability, though some components of the sustainability dimensions were impacted to some extent.

Table 9: Average Treatment Effect on the Treated (ATT) of Rainwater Harvesting and Fertilizer Micro-dosing Adoption in Dodoma, 2013–2016 (After matching algorithm applied)

Dependent variable:	**ATT**	sd	Mean Difference of the Matched Control Group	Sd
crop gross margin per ha	**29.25**	(48.54)	27.24	(32.55)
crop expenditures per ha	**165.86**	(16.44)	15.28*	(9.12)
labour productivity	**0.11**	(0.12)	-0.09	(0.08)
post-harvest loss	**-1.71**	(1.34)	-0.26	(0.74)
net household income	**-62.17**	(261.58)	1,455.45***	(210.33)
high income fluctuation	**0.01**	(0.08)	-0.02	(0.04)
has savings	**0.09***	(0.06)	0.61***	(0.04)
loss of income due to shock	**111.26**	(147.51)	67.57	(59.64)
high severity of shock	**0.06**	(0.08)	-0.06	(0.06)
months to recover after shock	**-4.52**	(6.29)	-10.29**	(4.26)
Potential Food Availability index (PFAI)	**0.07**	(0.3)	0.04	(0.22)
Months of inadequate food provisioning	**-0.13**	(0.57)	-0.96**	(0.38)
Food Consumption Score (FCS)	**2.80**	(2.87)	-1.52	(1.93)
Coping Strategies Index (CSI)	**1.20**	(3.54)	-25.94***	(2.64)
quantity of applied fertilizer	**-378.20**	(238.75)	467.07**	(206.55)
quantity of animal manure	**63.43**	(150.85)	-108.95	(94.44)
presence of irrigation	**-0.02**	(0.03)	0.01	(0.02)
rainfall water use efficiency	**0.13**	(0.08)	0.58***	(0.04)
change in household water consumption	**-38.49***	(20.4)	-15.97*	(9.63)
water harvesting	**0.55*****	(0.08)	-0.41***	(0.04)
water use conflict	**0.07***	(0.04)	-0.13***	(0.03)
crop performance index	**0.01**	(0.02)	-0.01	(0.01)
profitability index	**0.00**	(0.02)	0.02**	(0.01)
stability index	**-0.07**	(0.07)	0.29***	(0.05)
vulnerability to shocks reduction index	**-0.03**	(0.03)	0.06***	(0.02)
food security index	**0.01**	(0.03)	0.09***	(0.02)
soil management index	**0.00**	(0.02)	-0.05***	(0.02)
water management index	**0.01**	(0.02)	0.03**	(0.01)
agricultural diversity index	**-0.01**	(0.03)	-0.01	(0.02)
economic sustainability index	**-0.02**	(0.03)	0.09***	(0.02)
social sustainability index	**0.02**	(0.02)	-0.01	(0.01)
environmental sustainability index	**0.00**	(0.02)	-0.01	(0.01)
overall sustainability index	**0.00**	(0.02)	0.02**	(0.01)

*Note: *p<0.1; **p<0.05; ***p<0.01*

Table 10: Average Treatment Effect on the Treated (ATT) of Rainwater Harvesting and Fertilizer Micro-dosing Adoption in Morogoro, 2013–2016 (After matching algorithm applied)

Dependent variable:	**ATT**	Sd	Mean Difference of the Matched Control Group	sd
crop gross margin per ha	**-0.14**	(132.67)	-216.94**	(83.90)
crop expenditures per ha	**125.03**	(118.89)	-67.85	(113.13)
labour productivity	**0.24**	(0.26)	-0.49***	(0.17)
post-harvest loss	**0.44**	(1.08)	1.28**	(0.54)
net household income	**-81.08**	(203.42)	1,360.47***	(144.76)
high income fluctuation	**-0.04**	(0.09)	0.43***	(0.05)
has savings	**0.04**	(0.09)	0.32***	(0.05)
loss of income due to shock	**191.32**	(192.69)	656.39***	(71.33)
high severity of shock	**0.01**	(0.09)	0.46***	(0.05)
months to recover after shock	**23.12**	(50.72)	18.76	(14.68)
Potential Food Availability index (PFAI)	**-0.04**	(0.32)	0.19	(0.17)
Months of inadequate food provisioning	**-1.01**	(0.84)	-1.33***	(0.44)
Food Consumption Score (FCS)	**5.1***	(2.9)	-0.33	(1.42)
Coping Strategies Index (CSI)	**-9.72****	(4.53)	-7.38***	(1.90)
quantity of applied fertilizer	**-287.32**	(184.22)	288.19	(184.21)
quantity of animal manure	**12.50**	(10.44)	-12.51	(10.44)
presence of irrigation	**0.02**	(0.03)	0.03	(0.02)
rainfall water use efficiency	**-0.06**	(0.07)	0.5***	(0.05)
change in household water consumption	**-28.98***	(14.75)	8.75	(9.56)
water harvesting	**0.45*****	(0.08)	-0.04	(0.04)
water use conflict	**-0.01**	(0.04)	0.00	(0.02)
crop performance index	**0.03**	(0.03)	-0.10***	(0.01)
profitability index	**0.02**	(0.01)	-0.02**	(0.01)
stability index	**-0.09**	(0.07)	0.01	(0.04)
vulnerability to shocks reduction index	**0.02**	(0.04)	-0.14***	(0.02)
food security index	**0.10*****	(0.03)	0.04**	(0.02)
soil management index	**0.02**	(0.02)	0.01	(0.01)
water management index	**0.02**	(0.02)	-0.01	(0.01)
agricultural diversity index	**0.04***	(0.02)	0.06***	(0.01)
economic sustainability index	**0.01**	(0.03)	-0.06***	(0.02)
social sustainability index	**0.02**	(0.02)	-0.02*	(0.01)
environmental sustainability index	**0.03****	(0.01)	0.02***	(0.01)
overall sustainability index	**0.02**	(0.01)	-0.02**	(0.01)

*Note: *p<0.1; **p<0.05; ***p<0.01*

3.2.1. More savings in Dodoma and no impact on economic sustainability in both regions

In Dodoma, the households that adopted the innovations were more likely to increase their saving over the period 2013-2016 compared to the non adopters, even though the composite index for the economic sustainability and its component for economic stability were not affected by the treatment. Whereas in Morogoro, the composite index for the economic pillar of sustainability, economic stability and its components were not impacted significantly. In both regions the adoption of the innovations had no significant influence in the indicators and composite indices of crop profitability, profitability, and reduction of vulnerability to shocks.

3.2.2. More environmental sustainability in Morogoro and more water conflicts in Dodoma

The composite index for environmental sustainability significantly increased by 0.03 by the adoption of the innovations in Morogoro, while there was no impact in Dodoma. The composite water management index was not significantly impacted by the adoption of the innovations in Dodoma neither in Morogoro, but in Dodoma its component for water use conflict increased, and in both regions the change in household water consumption was impacted. The households that adopted the innovations in Dodoma reduced less the share of water for which they have conflicts, between the year 2013 and 2016, by 7% respect to the households that did not adopt them. In Dodoma, the households that adopted the innovations reduced the use of water by 38.48 additional daily litres compared to the houses that did not adopt, while in Morogoro, this reduction was by 28.98 additional daily litres. The adoption of the innovations had not significant effect on the presence of irrigation and rainfall use efficiency in both regions, and in water use conflict for Morogoro.

Respect the composite soil management index, the adoption of the innovations did not have a significant influence in Dodoma or Morogoro, and neither on the quantity of animal manure and fertilizer applied. Regarding, the impact on the agricultural diversity, in Morogoro this indicator had a higher increase between periods for the households that adopted the innovations, while there was no significant impact in Dodoma.

3.2.3. Improved food security in Morogoro and no impact in Dodoma

Respect to the food security in Dodoma, the adoption of the innovations rainwater harvesting and fertilizer micro-dosing did not make any significant difference on the results of the index or indicators that compose it. Also, the composite index for the social pillar of sustainability was not affected by the adoption of the innovations.

In Morogoro there was a significant increase on the food security index by the adoption of the innovations, though the composite index for the social pillar of sustainability was not impacted. The households that adopted the innovations increased their food security index by 0.1 additional points in comparison to the households that did not adopt. The households that adopted the innovations increased in 5 points more their Food Consumption Score. The Coping Strategies Index was impacted significantly as well, reducing by 9.7 points more when the households had adopted the innovations respect to the households that did not. The Potential Food Availability index was not significantly impacted, and neither the Months of inadequate food provisioning.

4. Discussion

The main objective of this research was to estimate the impact of the adoption of rainwater harvesting and fertilizer micro-dosing over the economic, social and environmental aspects of sustainability of households-farms of Dodoma and Morogoro regions of Tanzania. The results show that in the semi-humid region of Morogoro the adoption of the innovations improved households' environmental sustainability indicator by 0.1 and their food security indicator by 0.03, while the indicators for social sustainability and economic sustainability were not significantly impacted. In the semi-arid region of Dodoma there is surprisingly no impacts on households' composite indices for economic, social or environmental sustainability and food security, but water conflicts are higher for adopters by 7%, and they are more probable to have savings than the control group. Adopters of rainwater harvesting and fertilizer micro-dosing in Morogoro were characterized by a higher level of education and more land security, while adopters in Dodoma were characterized by assigning a lower proportion of land to cultivate cash-crops.

4.1. Morogoro: more food security linked to improved environmental sustainability but no economic results

In Morogoro, the increase in food security is related to an increase in the quantity and diversity of food consumed. The adoption of the innovations significantly improved the yields of maize (see Appendix 1 table 21), the most cultivated crop in the region, which meets the expectations of Graef et al. (2017) in their expert based ex-ante analysis for the innovations. The innovations would be tackling the problem of weather impacts that affected food security, as according to Gornott et al. (2017) 27% of the loss in maize yields in Tanzania was weather-related. Furthermore, the innovations appear to be optimizing the use of water in the region, the environmental sustainability is increased by less household water consumption and better managed irrigation water: retaining water during high rainfall and making it available during dry spells. The better environmental conditions supported by the innovations may also be promoting more diversity in the agricultural products of Morogoro, as shown by the positive impact in the agricultural diversity index; this agrees with other cases, like in northern Ethiopia where rainwater harvesting promoted the cultivation of root crops and vegetables in previously cereal-based regions (Biazin et al. 2012).

In this research, we could not find evidence that the increase in food security in Morogoro by the adoption of the innovations is explained by significant economic benefits, which shows that the innovations are not impacting sustainability in all the three pillars: economic, social, and environmental, if these aspects are evaluated in the same period of time. Nevertheless, we cannot assure that the results in this other pillar may not be achieved after a longer period, the study of van der Marck, E.J. (1999) indicates that under some conditions rainwater harvesting does not produce yields that are high enough to justify the investments in labour and materials, while in the long-run these investments could be covered by the economic gains and gross margins would be benefitted from the adoption of rainwater harvesting, (Ellis-Jones & Tengberg 2000). A limitation of this study may be the comparison between only two periods and the short time frame (only 3 years).

4.2. Dodoma: no food security or economic improvements motivated by uneven distribution of water, water conflicts, soil degradation, and poverty traps

In Dodoma, improvement in household food security with rainwater harvesting and fertilizer micro-dosing was expected due to its semi-arid climate, the income was projected to increase and food diversity to improve, according to the ex-ante assessment done by Graef et al. (2017). However, this could not be demonstrated, as the results here indicate that adopting rainwater harvesting and fertilizer micro-dosing had no significant impact in food security and economic sustainability in Dodoma. Uneven allocation of water, degraded natural resources, and poverty traps may be influencing on the absence of significant impact. Coping with droughts is related to food security and reducing poverty, however Enfors & Gordon (2008) also found lack of effects in stabilizing yields to cope with droughts from the adoption of another small-scale water system technology in semi-arid Tanzania. The authors suggested that the reason for the results is the substantial over-use of the irrigation system, explaining that water allocation among members in water use groups is uneven and some farmers receive water more frequently. This could be the case for our results if the adopters of rainwater harvesting have also adopted other water technology innovations. On the other hand, the research of Tittonell & Giller (2013) about yield gaps that become poverty traps in Africa, states that cropping continuously without the sufficient nutrients in the soil may degrade this resource up to the point it becomes non-responsive to fertilizer, driving smallholder farmers to a poverty trap. More research would be needed to this respect to determine if Dodoma requires further improvements for the productivity of their resources. Assets distribution could also generate a poverty trap, Kwak & Smith (2013) used non parametric techniques to assess the incidence of multiple equilibria in Ethiopia and found that differences in agricultural assets distribution generate two equilibria, leaving deprived regions in a low level stagnant equilibrium. The standard deviation of the value of productive assets shows considerable differences between farmers in Dodoma, so possibly innovations could work better for some household types and could have a significant impact.

The absence of impact on the economic indicator could be related to the high labour demand for applying these innovations and the opportunity costs of labour in Dodoma. The construction of tied ridges for cultivating under water harvesting requires 107.6 hours per person per acre, while flat cultivating requires only 24.3 hours per person per acre (Germer et al. 2021). Also, Pender et al. (2006) indicate that farmers are trying to combine fertilizer micro-dosing with seeds planting to cope with the labour intensity of fertilizer micro-dosing. In this research, turning to the household characteristics identified through the Sustainable Livelihoods Approach, high demand of labour from these practices may be connected to the increase of labour hours per hectare in Dodoma and Morogoro, however the region of Dodoma presented a higher percentage of labour working off-farm in the year 2013, which reduced for the year 2016. Therefore, an aspect to evaluate is the benefits that could be obtained from micro-dosing and water harvesting against the high labour requirements of the technique, which imply labour opportunity costs (Sieber et al. 2018; Habtemariam et al. 2019). Also, more economic support may be needed by farmers under Dodoma's conditions, Jansen et al. (2006a) agree on the need for policies prioritizing investments in asset bases for households that have a relatively high opportunity cost of labour like the ones that have off-farm employment, as a way to increase returns from assets and raise incomes.

Furthermore, the absence of improvements in economic sustainability of Dodoma could be indirectly related to the negative results in the indicator for water conflicts, Nyong (2005) states that the resource degradation motivates proneness to conflicts, which could be the case of the semi-arid region of Dodoma. Also, Vohland & Barry (2009) say that rainwater harvesting enhances water infiltration in the plots, but the reduced downstream runoff may generate conflicts between neighbours who compete for the water resources; conflicts may consume time, effort and resources.

The results from the study of Läpple & Thorne (2019) that state that a certain level of innovation must be reached before effects on economic sustainability can be evidenced, support that for the case of Dodoma it requires to combine the innovations assessed with others. This approach was proposed by the Trans-SEC project but here not addressed due to the lower number of adopters of the other technologies, innovations that may improve food security along with economic sustainability included adoption of post-harvest processing machines, byproducts use for bioenergy as well as better market linkages. Promoting policies that combine higher support for implementation of innovations with training may also be beneficial, as Jansen et al. (2006a) indicate that training has a direct positive effect on income improvements.

There was an economic indicator positively affected by the adoption of the innovations in Dodoma, that stated that adopters were more prompt to have savings than non-adopters. The explanation of this positive impact may be related to the perception of farmers that these innovations reduce the risk of water availability, which as Fox et al. (2005) state rainwater harvesting can reduce the risk of severe yield reduction over time, from 4 to 1 year out of 10 in their case study for Burkina Faso and Kenya. The authors also recognize that stability of yields promotes social resilience, but it is difficult to evaluate in economic terms, such as cost benefit analysis. Therefore, stability improvements could be better assessed in Dodoma considering the innovations' impact for longer periods of time and by a wider set of measures.

4.3. Benefits from the method: recognizing impacts on sustainability of more education and land security in Morogoro and lower cash-crop area in Dodoma

Without the application of any matching algorithm, the mean of the covariates between treated and non treated group was similar for many of them. However, some of the covariates are not balanced between the two groups without the matching and this highlights the importance of matching the groups to avoid biased conclusions on the effect of the treatment. Indeed, the simple comparison of the outcomes with the matching and without the matching, shows that some outcomes are rather different between the two approaches, supporting the decision to preliminary matching the groups (unmatched sample results in the Appendix 1 table

19 and 20). Adopters of the innovations in Dodoma tended to have a lower proportion of area dedicated to cash crops in comparison to non-adopters, and they underwent lower economic stability, economic sustainability, and money to invest in fertilizer and growth of new crops. This goes in accordance to what Maxwell & Fernando (1989) stated when they analysed the role of cash crops in developing countries, and they said that although there is a market risk from selling cash crops, selling a proportion of the output could help to offset the failure of subsistence crops.

Adopters of the innovations in Morogoro had higher land security and years of education, which influenced in the significant reduction of their Months of inadequate food provisioning. More adoption of innovations from farmers with the mentioned characteristics goes in line with literature, as Jansen et al. (2006a) concluded that the security in land tenure and education had a significant impact on the adoption of techniques and innovations. Furthermore, previous studies have also found a connection between higher levels of education and food security, this is thought to be related to more adoption of technologies and innovations for agriculture (Kebede et al. 1990), higher income and better knowledge of nutrition (De Cock et al. 2013). These findings support the implementation of policies that facilitate access to land ownership and education in Tanzania, sustained by their capacity to enhance food security.

The higher number of years of education of the household head and more land security of adopters in Morogoro may also be related to the reduction in the economic stability index, since farmers with higher levels of education are more likely to adopt innovative programmes and grow crops in more competitive markets for which they expect higher returns. This could be the case of sugarcane production in Morogoro, which was promoted by the Tanzanian government (Tanzania National Bureau of Statistics 2017). Morogoro is one of the biggest producers of sugarcane in Tanzania and in Kilosa farmers produce as outgrowers for the Kilombero Sugar Company (Chongela 2015), nevertheless the sugarcane industries tend to delay payments and reduce the price of the good due to cheap imports of sugar to Tanzania (Smalley et al. 2014).

4.4. Limitations of the study

Given the big range of sustainability measurement tools, a comparison to the results using a different measure could generate a deeper insight about their robustness. As mentioned earlier, the comparison between only two periods is another limitation, as the impacts on sustainability may not be evidenced for all pillars of sustainability after the same period of time. In addition, an analysis that separates household type could be the next step, which would allow to differentiate the results of the innovations on different households types under the same biophysical conditions of one region. This research gives space for new studies comparing the impact on sustainability of the same innovations but applied under different socio-economic and biophysical conditions, and measures to overcome poverty traps. Furthermore, a detailed analysis that explains the impact of the innovations on the decision of farmers to save and possible effects of the innovations on economic stability over time could be done.

5. Conclusions

This research supports the use of interdisciplinary assessments along with economic evaluations in intertemporal analysis, to evaluate the complementarity between economic, social and environmental sustainability. Assessments that cover the three pillars of sustainability are recommended to complement the implementation of agricultural technologies, before and after their use, to recognize the need of improvement and supplementing actions. Future research for a longer period of time and possibly considering other methods to make an ex-post sustainability assessment of these innovations could enrich the debate.

The results of this research highlight the importance of implementing agricultural technologies, and policies associated to them, targeting at the specific characteristics and needs of the regions in which the farms are operating. For the case of semi-humid regions like Morogoro, disseminating the innovations rainwater harvesting and fertilizer micro-dosing proved to promote environmental sustainability and ensure food security through more diversity and quantity of food. Nevertheless, to observe economic benefits from the adoption of the innovations, the analysis may need to cover a longer period of time. While for the case of regions like semi-arid Dodoma, it may be worth looking for alternative technologies and complementing policies, given that no significant impact could be found from the adoption of rainwater harvesting and fertilizer micro-dosing over social, economic and environmental sustainability of households and farms. For instance, the characteristics not balanced according to the Propensity Score Matching method allowed to recognize that policies promoting cultivation of cash-crops, more education and land security, can benefit food security and economic results. Furthermore, counterproductive impacts of agricultural innovations should be controlled and may be recognized by follow-up assessments to the application of new technologies, as in this case water conflicts were exacerbated by the adoption of the innovations in Dodoma.

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Appendix 1

Table 11: Summary statistics of household characteristics of Dodoma

		Dodoma 2013					Dodoma 2016					**Difference 2016 - 2013**
Variable	Units	n	**mean**	sd	min	max	n	**mean**	sd	min	max	
Family size	No. people	448	**5.3**	2.2	1	18	420	**5.5**	2.2	1	12	**0.2**
Age of household head	Years	447	**49**	16.9	22	110	420	**51.2**	16.9	22	100	**2.2**
Female household head	Yes-No	448	**0.2**	0.4	0	1	420	**0.2**	0.4	0	1	**0**
Experience of household head	Years	448	**20.5**	17.2	0.8	84	420	**20.7**	13.6	1	77	**0.2**
Education of household head	Years	424	**4.2**	3.4	0	16	415	**4.4**	3.5	0	14	**0.2**
Household female literacy	%	436	**0.5**	0.5	0	1	407	**0.6**	0.4	0	1	**0.1**
Total labour invested per land unit	hours/ha	448	**562.4**	748.4	16.4	9452	420	**651.3**	508.8	73.3	5647.1	**88.9**
Share of hired labour in total labour	%	448	**0.1**	0.1	0	1	420	**0.1**	0.2	0	0.9	**0**
Share of total labour working in land preparation	%	448	**0.2**	0.2	0	0.8	420	**0.2**	0.1	0	0.8	**0**
Share of total labour working in weeding	%	448	**0.3**	0.2	0	1.1	420	**0.3**	0.1	0	0.8	**0**
Share of total labour working in harvesting	%	448	**0.2**	0.2	0	2.2	420	**0.2**	0.1	0	1	**0**
Share of total labour working in planting	%	448	**0.1**	0.1	0	0.6	420	**0.1**	0.1	0	0.4	**0**
Share of total labour working in other cropping activities	%	448	**0.1**	0.1	0	0.8	420	**0.1**	0.1	0	0.3	**0**

Active members on-farm	%	375	**1**	0.1	0.2	1	406	**1**	0.1	0.2	1	**0**
Active members off-farm	%	446	**0.4**	0.4	0	1	420	**0.3**	0.4	0	1	**-0.1**
Total area managed by the household	Ha	448	**2.4**	2.4	0.2	32.1	420	**2.5**	3.6	0.2	61.3	**0.1**
Share of total area rented in	%	448	**0.1**	0.2	0	1	420	**0.1**	0.2	0	1	**0**
Share of crop land managed remotely	%	442	**0.4**	0.4	0	1	409	**0.3**	0.4	0	1	**-0.1**
Share of total area perceived by the household as fertile	%	448	**0.3**	0.4	0	1	420	**0.6**	0.4	0	1	**0.3**
Affected by drought	Yes-No	448	**0.7**	0.5	0	1	420	**0.5**	0.5	0	1	**-0.2**
Share of total area used for cropping	%	448	**0.9**	0.2	0	1	420	**0.8**	0.2	0	1	**-0.1**
Share of cropped area dedicated to grassland	%	448	**0**	0	0	0.9	420	**0**	0	0	0.8	**0**
Share of cropped area dedicated to cash crops	%	448	**0.1**	0.2	0	1	420	**0.2**	0.2	0	0.8	**0.1**
Share of cropped area dedicated to maize	%	448	**0.1**	0.1	0	0.8	420	**0.2**	0.2	0	1	**0.1**
Share of cropped area dedicated to bullrush	%	448	**0.3**	0.3	0	1	420	**0.3**	0.3	0	1	**0**
Share of cropped area dedicated to other cereals	%	448	**0.2**	0.3	0	1	420	**0.2**	0.3	0	1	**0**
Share of cropped area dedicated to legumes	%	448	**0.3**	0.2	0	1	420	**0.2**	0.2	0	1	**-0.1**
Share of cropped area dedicated to other crops	%	448	**0**	0.1	0	0.6	420	**0**	0.1	0	1	**0**
Share of cropped area dedicated to cereals	%	448	**0.6**	0.2	0	1	420	**0.6**	0.2	0	1	**0**
Cropped area irrigated	Yes-No	448	**0**	0	0	0.3	420	**0**	0	0	0.4	**0**
Value of fertilizer and pesticide expenditures	USD/ha	448	**2.8**	11	0	125.8	420	**8.3**	44.2	0	822.9	**5.5**
Household Tropical Livestock Units (TLU)	TLU	448	**1.4**	2.7	0	21	420	**1.3**	2.8	0	28.7	**-0.1**
Size of poultry herd	TLU	448	**0**	0.1	0	0.6	420	**0.1**	0.1	0	1.2	**0.1**

Size of goat and sheep herd	TLU	448	**0.2**	0.7	0	8	420	**0.2**	0.4	0	5	**0**
Size of pig herd	TLU	448	**0.1**	0.2	0	2.2	420	**0.1**	0.3	0	2.4	**0**
Size of cattle herd	TLU	448	**1**	2.3	0	18.9	420	**1**	2.5	0	27.3	**0**
Share of crop production sold	%	448	**0.1**	0.2	0	1	420	**0.2**	0.2	0	1	**0.1**
Share of household income generated by crop production	%	448	**0.3**	0.3	0	1	420	**0.4**	0.3	0	1.2	**0.1**
Share of household income generated by livestock production	%	448	**0.2**	0.3	0	1	420	**0.2**	0.2	0	1	**0**
Share of household income generated by off-farm employment	%	448	**0.1**	0.2	0	1	420	**0.1**	0.2	0	1	**0**
Share of household income generated by self-employment	%	448	**0.1**	0.2	0	1	420	**0.2**	0.3	0	1	**0.1**
Share of household income generated by hunting/gathering	%	448	**0.2**	0.3	0	1	420	**0**	0.1	-0.2	1	**-0.2**
Share of household income from remittances	%	448	**0**	0.1	0	0.7	420	**0.1**	0.2	0	1	**0.1**
Share of household income from social support systems	%	448	**0**	0.1	0	0.8	420	**0**	0.1	0	1	**0**
Share of household income generated by off-farm activities	%	448	**0.5**	0.3	0	1	420	**0.4**	0.3	-0.2	1	**-0.1**
Value of loans	USD	448	**33.5**	163.2	0	2545.4	420	**41.8**	308	0	5904.2	**8.3**
Value of household expenditures	USD	448	**1432.7**	1072.8	0	5790.2	420	**1496.4**	1418	93.9	19315.1	**63.7**
Value of food expenditures	USD	448	**855.2**	702.6	0	4288.4	420	**993.7**	1153.6	0.3	18421.2	**138.5**
Number of ploughs	No.	448	**0.3**	0.6	0	5	420	**0.3**	0.6	0	3	**0**
Number of stoves	No.	448	**0.1**	0.3	0	2	420	**0.1**	0.4	0	4	**0**
Number of mobile phones	No.	448	**0.5**	0.8	0	4	420	**0.8**	0.9	0	5	**0.3**
Value of productive assets	USD	448	**73.1**	161.6	0	2358.3	420	**75.9**	276.2	0	4879.3	**2.8**
Value of household assets	USD	448	**153.8**	339.3	0	3347.1	420	**219.2**	449.6	0	3457.5	**65.4**

Table 12: Summary statistics of household characteristics of Morogoro

		Morogoro 2013					Morogoro 2016					**Difference 2016 - 2013**
Variable	Units	n	**mean**	sd	min	max	n	**mean**	sd	min	max	
Family size	No. people	444	**4.4**	2.3	1	13	391	**5**	2.4	1	19	**0.6**
Age of household head	Years	443	**47.9**	17	19	116	391	**50.8**	16	22	100	**2.9**
Female household head	Yes-No	444	**0.2**	0.4	0	1	391	**0.2**	0.4	0	1	**0**
Experience of household head	Years	444	**13.3**	11.8	1	82	391	**16.8**	12.4	2	87	**3.5**
Education of household head	Years	440	**4.9**	3.3	0	14	390	**4.8**	3.3	0	17	**-0.1**
Household female literacy	%	409	**0.7**	0.4	0	1	372	**0.6**	0.4	0	1	**-0.1**
Total labour invested per land unit	hours/ha	444	**653.2**	737	21	9866.7	389	**699.9**	553.1	0	3632.4	**46.7**
Share of hired labour in total labour	%	444	**0.2**	0.3	0	1	390	**0.2**	0.3	0	1	**0**
Share of total labour working in land preparation	%	444	**0.3**	0.2	0	0.8	390	**0.2**	0.2	0	0.8	**-0.1**
Share of total labour working in weeding	%	444	**0.3**	0.2	0	2.1	390	**0.3**	0.2	0	1.3	**0**
Share of total labour working in harvesting	%	444	**0.2**	0.1	0	0.9	390	**0.2**	0.2	0	1.1	**0**
Share of total labour working in planting	%	444	**0.1**	0.1	0	0.8	390	**0.1**	0.1	0	0.7	**0**
Share of total labour working in other cropping activities	%	444	**0.1**	0.1	0	0.8	390	**0.1**	0.1	0	0.5	**0**
Active members on-farm	%	392	**1**	0.1	0.2	1	376	**1**	0.1	0.3	1	**0**
Active members off-farm	%	442	**0.2**	0.4	0	1	391	**0.3**	0.4	0	1	**0.1**
Total area managed by the household	Ha	444	**2.1**	1.9	0.1	24.3	391	**2.5**	5.1	0.1	93.1	**0.4**
Share of total area rented in	%	444	**0.2**	0.3	0	1	391	**0.1**	0.3	0	1	**-0.1**
Share of crop land managed remotely	%	430	**0.3**	0.4	0	1	380	**0.2**	0.4	0	1	**-0.1**
Share of total area perceived by the household as fertile	%	444	**0.5**	0.5	0	1	391	**0.6**	0.4	0	1	**0.1**
Affected by drought	Yes-No	444	**0.1**	0.3	0	1	391	**0.3**	0.5	0	1	**0.2**

Share of total area used for cropping	%	444	**0.8**	0.2	0	1	391	**0.8**	0.3	0	1	**0**
Share of cropped area dedicated to grassland	%	444	**0**	0.1	0	1	391	**0**	0	0	0	**0**
Share of cropped area dedicated to cash crops	%	444	**0.2**	0.3	0	1	391	**0.2**	0.2	0	0.9	**0**
Share of cropped area dedicated to maize	%	444	**0.6**	0.3	0	1	391	**0.4**	0.3	0	1	**-0.2**
Share of cropped area dedicated to bullrush	%	444	**0**	0	0	0.2	391	**0.1**	0.2	0	1	**0.1**
Share of cropped area dedicated to other cereals	%	444	**0.1**	0.2	0	1	391	**0.1**	0.2	0	1	**0**
Share of cropped area dedicated to legumes	%	444	**0.1**	0.1	0	0.8	391	**0.2**	0.2	0	0.8	**0.1**
Share of cropped area dedicated to other crops	%	444	**0**	0.1	0	1	391	**0**	0.1	0	0.5	**0**
Share of cropped area dedicated to cereals	%	444	**0.7**	0.3	0	1	391	**0.6**	0.2	0	1	**-0.1**
Cropped area irrigated	Yes-No	444	**0**	0.1	0	1	391	**0**	0.1	0	1	**0**
Value of fertilizer and pesticide expenditures	USD/ha	444	**12.5**	77.9	0	1028.4	391	**12.1**	31.2	0	330.7	**-0.4**
Household Tropical Livestock Units (TLU)	TLU	444	**0.3**	1.7	0	21.6	391	**0.7**	2.5	0	40.2	**0.4**
Size of poultry herd	TLU	444	**0.1**	0.2	0	2.2	391	**0.1**	0.1	0	0.9	**0**
Size of goat and sheep herd	TLU	444	**0.1**	0.5	0	10	391	**0.1**	0.8	0	11	**0**
Size of pig herd	TLU	444	**0**	0.1	0	2	391	**0**	0.2	0	2.4	**0**
Size of cattle herd	TLU	444	**0.2**	1.6	0	19.6	391	**0.4**	1.9	0	29.4	**0.2**
Share of crop production sold	%	444	**0.4**	0.3	0	1	391	**0.4**	0.3	0	1	**0**
Share of household income generated by crop production	%	444	**0.6**	0.3	0	1	391	**0.5**	0.4	0	1	**-0.1**
Share of household income generated by livestock production	%	444	**0.1**	0.2	0	1	391	**0.1**	0.2	0	1	**0**

Share of household income generated by off-farm employment	%	444	**0**	0.1	0	0.9	391	**0.1**	0.2	0	1	**0.1**
Share of household income generated by self-employment	%	444	**0.1**	0.2	0	1	391	**0.2**	0.3	0	1	**0.1**
Share of household income generated by hunting/gathering	%	444	**0.1**	0.2	0	1	391	**0**	0.1	0	1	**-0.1**
Share of household income from remittances	%	444	**0**	0.1	0	1	391	**0.1**	0.2	0	1	**0.1**
Share of household income from social support systems	%	444	**0**	0	0	0.7	391	**0**	0.1	0	1	**0**
Share of household income generated by off-farm activities	%	444	**0.3**	0.3	0	1	391	**0.4**	0.4	0	1	**0.1**
Value of loans	USD	444	**50.1**	466.2	0	8908.7	391	**50.7**	206.5	0	2361.7	**0.6**
Value of household expenditures	USD	444	**1637**	1539.5	0	11153.7	390	**1618.6**	1127.9	29.5	8549.3	**-18.4**
Value of food expenditures	USD	444	**968.9**	926.4	0	7676.8	390	**1054.6**	766.7	0	4298.3	**85.7**
Number of ploughs	No.	444	**0**	0.1	0	1	391	**0.1**	0.3	0	3	**0.1**
Number of stoves	No.	444	**0.2**	0.4	0	4	391	**0.2**	0.5	0	2	**0**
Number of mobile phones	No.	444	**0.7**	0.8	0	5	391	**0.9**	0.8	0	4	**0.2**
Value of productive assets	USD	444	**29.9**	63.1	0	603.2	391	**63.7**	331.9	0	6197.1	**33.8**
Value of household assets	USD	444	**215.5**	444.3	0	3958	391	**320.7**	622.3	0	5845.2	**105.2**

Table 13: Summary statistics of sustainability indicators for Dodoma

Pillar	Component	Indicator	Dodoma 2013 (n = 448) Mean	CV (%)	Dodoma 2016 (n = 420) mean	CV (%)	Difference 2016 - 2013
Environmental	Soil management	Quantity of bought fertilizer	157.7	484	611.8	740	454.1
		Quantity of animal manure	135.8	580	82.4	592	-53.4
		Crop area perceived as unfertile	0.2	200	0	0	-0.2
		Crop area with perceived decrease in fertility	0.6	67	0.5	80	-0.1
		Crop area under legume	0.3	67	0.2	100	-0.1
		Crop residues left on the field	0.3	133	0.2	150	-0.1
		Intent to invest in soil fertility	0.8	50	0.5	80	-0.3
		Tree density	11.4	532	9.4	400	-2
		Area under erosion control measures	0.3	133	0.2	200	-0.1
	Water management	Presence of irrigation	0	0	0	0	0
		Rainfall water use efficiency	0.5	200	0.6	117	0.1
		Change in water consumption	7.1	549	-20.9	-642	-28
		Water harvesting	0.4	125	0.2	200	-0.2
		Water use conflict	0.1	300	0	0	-0.1
	Agricultural diversity	Tree diversity	2.9	83	2.8	64	-0.1
		Crop diversity	3.7	43	3.3	39	-0.4
		Livestock diversity	1.3	100	1.8	72	0.5
Economic	Crop profitability	Crop gross margin	159	229	206.4	129	47.4
		Crop expenditures	35.8	206	53.4	171	17.6
		Labour productivity	0.6	217	0.5	100	-0.1
		Post-harvest loss	3.1	319	2.1	205	-1
	Profitability	Net household income	982.5	133	1368.8	126	386.3
	Stability	High income fluctuation	0.5	100	0.5	100	0
		Has savings	0.2	200	0.8	50	0.6
	Vulnerability to shocks	Loss of income due to shock	349.6	202	424.4	161	74.8
		High severity of shock	0.7	57	0.7	71	0
		Time to recover after shock	25.6	130	18.5	588	-7.1

Social	Food security	Potential Food Availability index (PFAI)	2	75	2	140	0
		Months of inadequate food provisioning	5.8	62	4.8	77	-1
		Food Consumption Score (FCS)	45.8	35	46.9	38	1.1
		Coping Strategies Index (CSI)	33.8	88	6.3	244	-27.5
	Health	Health insurance binary	0.3	133	0.3	167	0
		Healthy household members	0.8	37	0.8	25	0
	Wellbeing	Hours worked	664.3	120	707.2	97	42.9
		Perceived deterioration of household situation	0.5	100	0.4	125	-0.1
		High impact of income fluctuations on wellbeing	0.5	100	0.4	125	-0.1
	Social capital	Information network	34.2	142	14.3	99	-19.9
		% of crops receiving support from farmers group	0.1	300	0.1	200	0
	Land security	Land title ownership	0	0	0	0	0
		Secure land	0.5	100	0.5	100	0
		Land use conflict	0.1	200	0	0	-0.1

Table 14: Summary statistics of sustainability indicators for Morogoro

Pillar	Component	Indicator	Morogoro 2013 (n = 444) mean	Morogoro 2013 (n = 444) CV (%)	Morogoro 2016 (n = 391) mean	Morogoro 2016 (n = 391) CV (%)	Difference 2016 - 2013
Environmental	Soil management	Quantity of bought fertilizer	2	930	298.4	1424	296.4
		Quantity of animal manure	26	1316	0.5	1240	-25.5
		Crop area perceived as unfertile	0.1	200	0	0	-0.1
		Crop area with perceived decrease in fertility	0.5	100	0.3	133	-0.2
		Crop area under legume	0.1	100	0.2	100	0.1
		Crop residues left on the field	0.4	125	0.1	200	-0.3
		Intent to invest in soil fertility	0.3	167	0.3	133	0
		Tree density	4.6	165	7.9	194	3.3
		Area under erosion control measures	0.2	150	0.2	150	0
	Water management	Presence of irrigation	0	0	0.1	300	0.1
		Rainfall water use efficiency	0.7	243	0.5	160	-0.2
		Change in water consumption	1.1	3573	-2.5	-3328	-3.6
		Water harvesting	0.1	300	0.2	200	0.1
		Water use conflict	0.1	200	0	0	-0.1
	Agricultural diversity	Tree diversity	1.8	100	2.4	67	0.6
		Crop diversity	2.1	48	2.8	39	0.7
		Livestock diversity	0.8	87	0.9	67	0.1
Economic	Crop profitability	Crop gross margin	609.3	175	391	210	-218.3
		Crop expenditures	195.8	589	191.8	173	-4
		Labour productivity	1.6	125	1.1	173	-0.5
		Post-harvest loss	1.8	322	3.5	249	1.7
	Profitability	Net household income	1483.9	187	1396.2	117	-87.7
	Stability	High income fluctuation	0.3	133	0.6	83	0.3
		Has savings	0.4	125	0.7	71	0.3
	Vulnerability to shocks	Loss of income due to shock	155.8	274	768.2	136	612.4
		High severity of shock	0.4	125	0.8	50	0.4
		Time to recover after shock	11.9	223	48	691	36.1

Social	Food security	Potential Food Availability index (PFAI)	2.7	78	2.7	74	0
		Months of inadequate food provisioning	5.1	96	4	88	-1.1
		Food Consumption Score (FCS)	53.2	31	53.8	29	0.6
		Coping Strategies Index (CSI)	16.2	149	7.3	225	-8.9
	Health	Health insurance binary	0.1	300	0.2	200	0.1
		Healthy household members	0.9	33	0.8	37	-0.1
	Wellbeing	Hours worked	532.1	154	627	124	94.9
		Perceived deterioration of household situation	0.3	167	0.6	83	0.3
		High impact of income fluctuations on wellbeing	0.2	200	0.5	100	0.3
	Social capital	Information network	16.3	133	28.1	142	11.8
		% of crops receiving support from farmers group	0.3	133	0.1	300	-0.2
	Land security	Land title ownership	0.1	300	0	0	-0.1
		Secure land	0.1	300	0.3	133	0.2
		Land use conflict	0.1	300	0.1	300	0

Table 15: Summary of Balance after matching in Dodoma

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
distance	0.2707	0.2706	0.0017	1.0129	
Age of household head	49.4746	49.5673	-0.0061	0.7636	0.79
Education of household head	4.2461	4.2270	0.0061	0.8023	0.62
Total labour invested per land unit	559.2268	506.6087	0.0738	1.6210	0.88
Total area managed by the household	2.5440	3.4118	-0.4118	0.0971	0.20
Share of total area used for cropping	0.8861	0.8570	0.1497	0.5967	0.22
Share of cropped area dedicated to cash crops	0.0958	0.1084	-0.0981	0.6692	0.10
Value of productive assets	74.5890	71.2062	0.0137	0.5643	0.22

Table 16: Summary of Balance before matching in Dodoma

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
distance	0.2786	0.2560		1.6411	
Age of household head	49.5253	49.6839	-0.0104	0.7979	0.93
Education of household head	4.2485	4.1363	0.0359	0.8491	0.75
Total labour invested per land unit	576.7159	570.0373	0.0094	0.8231	0.93
Total area managed by the household	2.6264	2.3446	0.1337	0.7086	0.25
Share of total area used for cropping	0.8881	0.8521	0.1855	0.5883	0.13
Share of cropped area dedicated to cash crops	0.0965	0.1227	-0.2030	0.5781	0.09
Value of productive assets	101.8320	66.0513	0.1452	3.8705	0.15

Table 17: Summary of Balance after matching in Morogoro

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
distance	0.1962	0.1959	0.0036	1.0248	
Age of household head	47.4062	47.8877	-0.0287	0.7572	0.71
Education of household head	5.3895	5.3423	0.0159	0.9639	0.44
Hired labour	0.1314	0.1378	-0.0263	1.2641	0.72
Total area managed by the household	2.3341	2.0173	0.1841	1.2238	0.12
Share of total area used for cropping	0.8764	0.8704	0.0286	1.3000	0.97
Share of cropped area dedicated to cash crops	0.2344	0.2231	0.0417	1.1916	0.81
Share of cropped area dedicated to maize	0.5881	0.5811	0.0223	1.3078	0.64
Total labour invested per land unit	646.5104	707.4235	-0.0980	0.4708	0.71
Land security index	0.3936	0.4079	-0.0657	1.2461	0.80

Table 18: Summary of Balance before matching in Morogoro

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
distance	0.2149	0.1698	0.4411	2.0307	
Age of household head	49.3043	47.7962	0.0900	0.9903	0.50
Education of household head	5.5062	4.8174	0.2320	0.7796	0.09
Hired labour	0.1295	0.1720	-0.1726	0.8696	0.20
Total area managed by the household	2.4046	2.0263	0.2197	0.7600	0.11
Share of total area used for cropping	0.8808	0.8519	0.1385	0.8944	0.30
Share of cropped area dedicated to cash crops	0.2174	0.2217	-0.0158	1.1236	0.90
Share of cropped area dedicated to maize	0.5932	0.6271	-0.1077	1.2415	0.41
Total labour invested per land unit	641.1608	656.3226	-0.0244	0.6132	0.86
Land security index	0.4185	0.3715	0.2160	1.9580	0.09

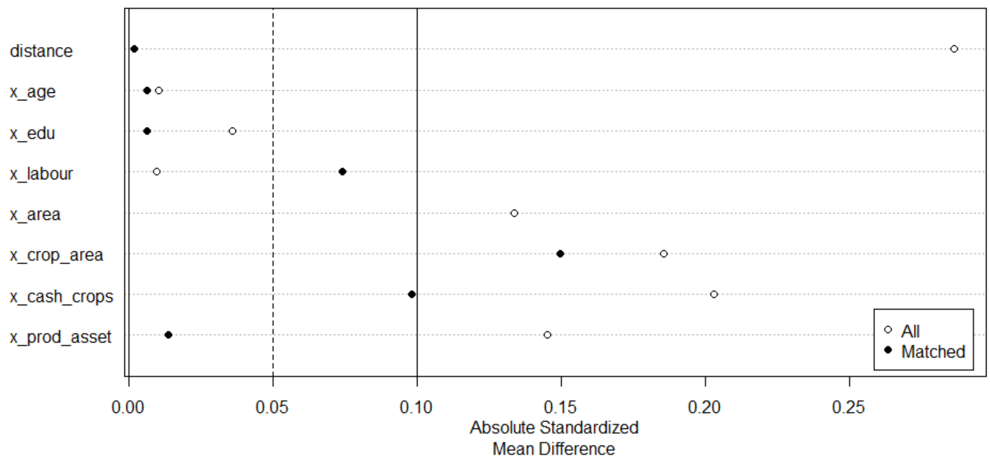

Figure 3:Absolute Standardized Mean Differences of matched sample from Dodoma

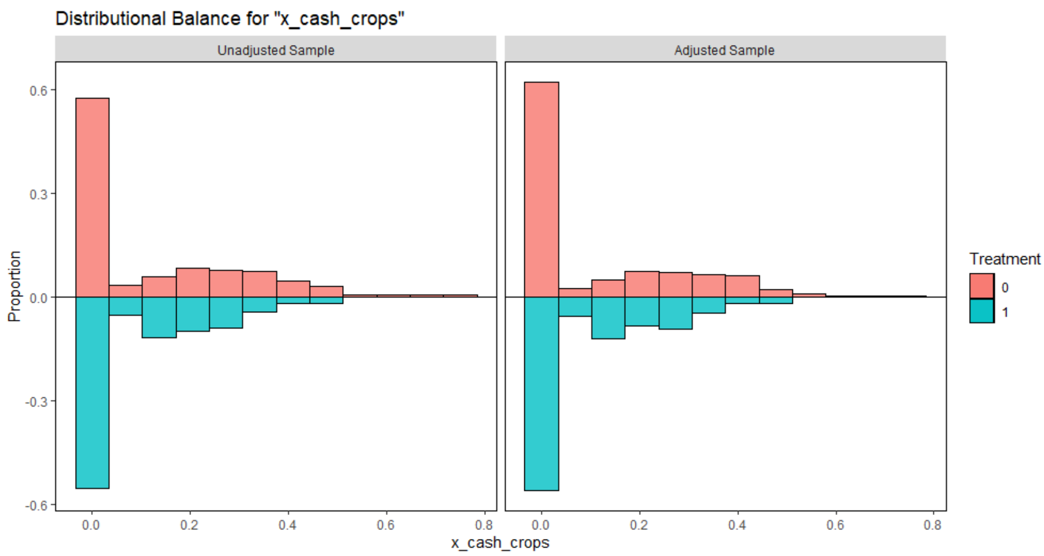

Figure 4:Distributional Balance for "share of cash crops" covariate before and after matching in Dodoma

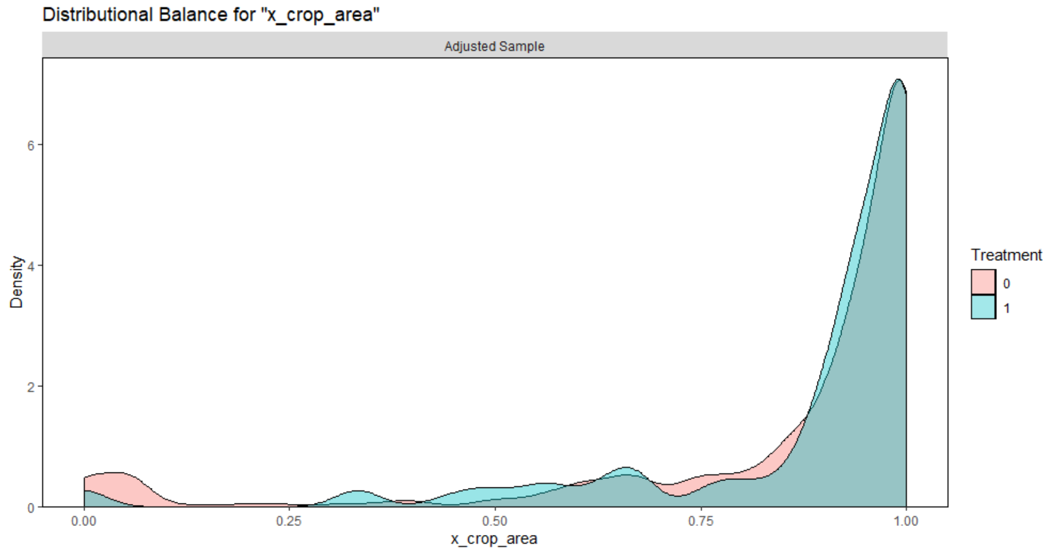

Figure 5:Distributional Balance for "percentage of total area used for cropping" covariate after matching in Dodoma

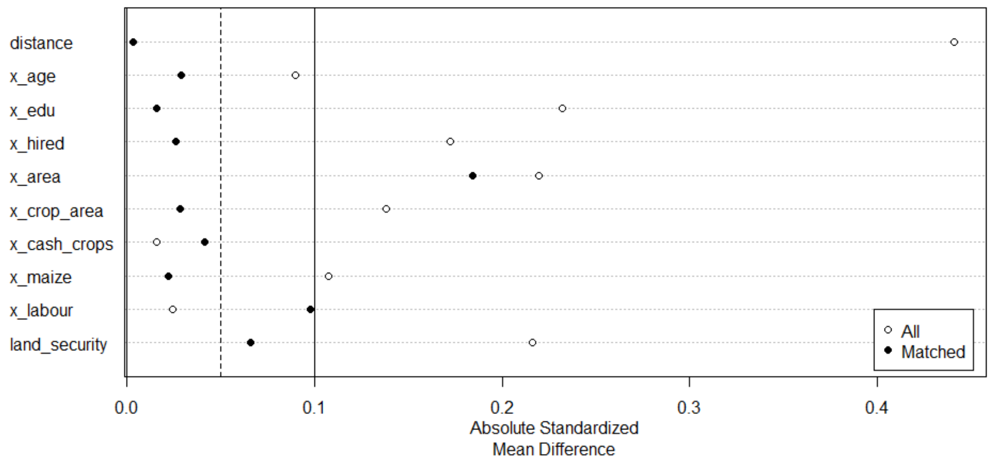

Figure 6:Absolute Standardized Mean Differences of matched sample from Morogoro

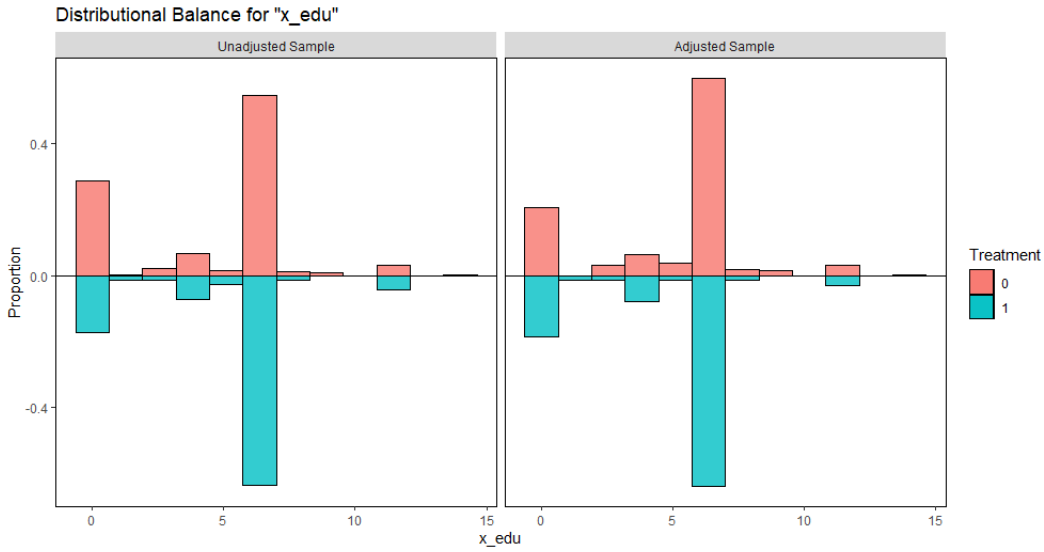

Figure 7:Distributional Balance for "education of the household head" covariate before and after matching in Morogoro

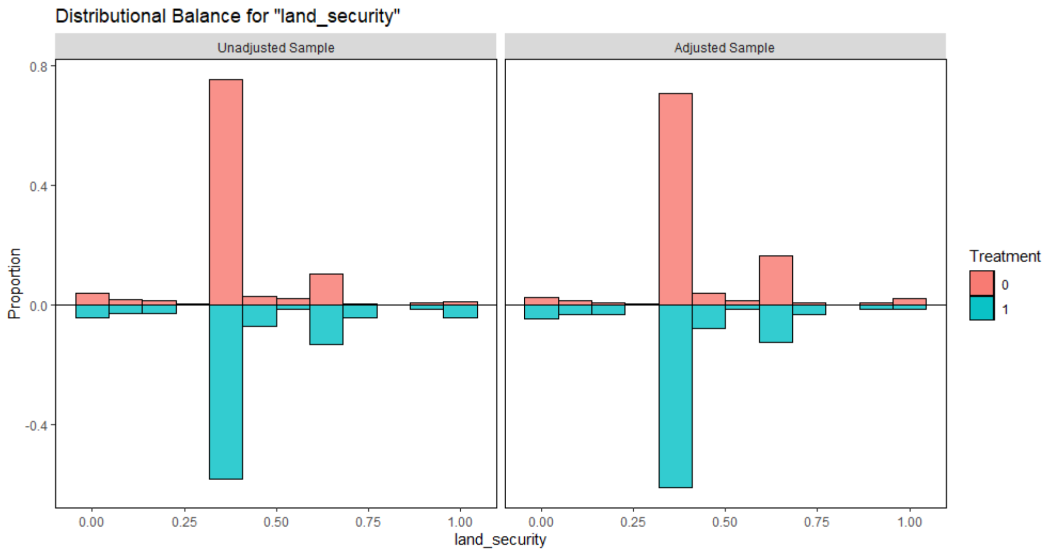

Figure 8: Distributional Balance for "land security indicator" covariate before and after matching in Morogoro

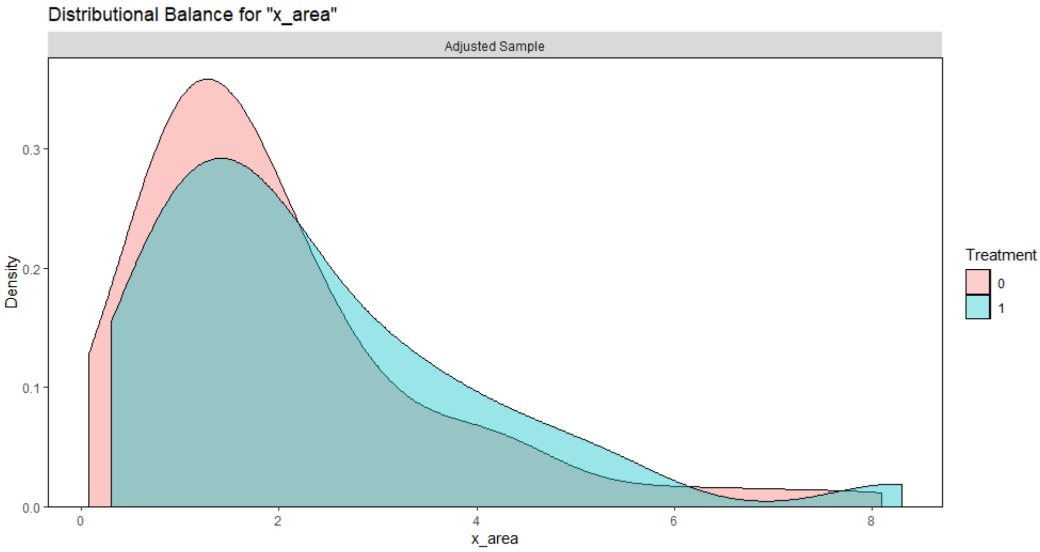

Figure 9:Distributional Balance for "total area managed by the household" covariate after matching in Morogoro

Table 19: Average Treatment Effect on the Treated (ATT) of Rainwater Harvesting and Fertilizer Micro-dosing Adoption in Dodoma, 2013–2016 (Before matching algorithm applied)

Dependent variable:	ATT	Mean Difference of the Matched Control Group
crop gross margin per ha	0.751	56.834**
	(41.543)	(22.328)
crop expenditures per ha	17.268	14.844**
	(14.618)	(5.953)
labour productivity	0.065	-0.044
	(0.106)	(0.062)
post-harvest loss	-1.266	-0.710
	(1.250)	(0.619)
net household income	40.564	1,357.252***
	(181.942)	(100.617)
high income fluctuation	0.083	-0.074*
	(0.082)	(0.038)
has savings	0.113*	0.587***
	(0.059)	(0.030)
loss of income due to shock	145.927	37.416
	(138.566)	(44.432)
high severity of shock	0.039	-0.039
	(0.071)	(0.037)
months to recover after shock	14.187	-10.523***
	(19.192)	(3.377)
Potential Food Availability index (PFAI)	0.119	-0.004
	(0.273)	(0.198)
Months of inadequate food provisioning	-0.064	-1.000***
	(0.514)	(0.294)
Food Consumption Score (FCS)	-0.222	1.177
	(2.437)	(1.144)
Coping Strategies Index (CSI)	4.173	-28.677***
	(3.006)	(1.934)
quantity of applied fertilizer	-614.812*	617.224**
	(332.265)	(299.069)
quantity of animal manure	19.725	-64.000
	(123.324)	(46.050)
presence of irrigation	-0.025	0.016
	(0.021)	(0.013)
rainfall water use efficiency	0.112	0.591***
	(0.075)	(0.037)
change in household water consumption	-33.833*	-18.958**
	(19.236)	(7.608)
water harvesting	0.560***	-0.397***
	(0.069)	(0.030)
water use conflict	0.067**	-0.128***
	(0.033)	(0.021)

crop performance index	-0.004	0.003
	(0.015)	(0.007)
profitability index	-0.060	0.072***
	(0.037)	(0.020)
stability index	-0.105*	0.327***
	(0.055)	(0.028)
vulnerability to shocks reduction index	-0.036	0.063***
	(0.025)	(0.015)
food security index	-0.017	0.114***
	(0.023)	(0.012)
soil management index	-0.008	-0.035***
	(0.019)	(0.010)
water management index	0.002	0.025***
	(0.017)	(0.009)
agricultural diversity index	-0.035*	0.009
	(0.020)	(0.010)
economic sustainability index	-0.051**	0.116***
	(0.020)	(0.011)
social sustainability index	0.005	0.002
	(0.016)	(0.008)
environmental sustainability index	-0.014	-0.0003
	(0.013)	(0.006)
overall sustainability index	-0.020	0.039***
	(0.012)	(0.006)

*Note: *p<0.1; **p<0.05; ***p<0.01*

Table 20:Average Treatment Effect on the Treated (ATT) of Rainwater Harvesting and Fertilizer Micro-dosing Adoption in Morogoro, 2013–2016 (Before matching algorithm applied)

Dependent variable:	ATT	Mean Difference of the Matched Control Group
crop gross margin per ha	-15.338	-217.204**
	(129.892)	(84.525)
crop expenditures per ha	89.990	-35.627
	(84.194)	(76.993)
labour productivity	0.295	-0.559***
	(0.249)	(0.168)
post-harvest loss	0.828	1.684***
	(1.391)	(0.540)
net household income	-105.797	1,419.753***
	(171.051)	(96.755)
high income fluctuation	-0.033	0.395***
	(0.082)	(0.036)
has savings	0.025	0.323***
	(0.079)	(0.035)
loss of income due to shock	301.302	558.606***
	(185.991)	(53.209)
high severity of shock	0.014	0.464***
	(0.080)	(0.032)
months to recover after shock	2.820	36.066**
	(48.595)	(18.271)
Potential Food Availability index (PFAI)	-0.177	0.084
	(0.345)	(0.122)
Months of inadequate food provisioning	-1.744**	-0.720**
	(0.755)	(0.324)
Food Consumption Score (FCS)	5.028*	-0.231
	(2.698)	(1.091)
Coping Strategies Index (CSI)	-9.685**	-7.246***
	(4.231)	(1.539)
quantity of applied fertilizer	-362.841	362.992
	(263.536)	(263.530)
quantity of animal manure	-19.451	-24.389
	(46.477)	(20.719)
presence of irrigation	0.012	0.031**
	(0.036)	(0.015)
rainfall water use efficiency	-0.100	0.532***
	(0.068)	(0.046)
change in household water consumption	-23.968**	1.720
	(11.844)	(5.307)
water harvesting	0.404***	-0.013
	(0.076)	(0.024)
water use conflict	0.026	-0.010
	(0.045)	(0.016)

crop performance index	0.017	-0.094***
	(0.025)	(0.010)
profitability index	0.044	0.018
	(0.059)	(0.022)
stability index	-0.105*	0.033
	(0.062)	(0.028)
vulnerability to shocks reduction index	0.002	-0.124***
	(0.033)	(0.014)
food security index	0.094***	0.040***
	(0.027)	(0.013)
soil management index	0.014	0.017**
	(0.017)	(0.008)
water management index	0.005	0.004
	(0.021)	(0.008)
agricultural diversity index	0.028	0.067***
	(0.019)	(0.009)
economic sustainability index	-0.011	-0.042***
	(0.026)	(0.012)
social sustainability index	0.012	-0.020***
	(0.015)	(0.007)
environmental sustainability index	0.016	0.030***
	(0.012)	(0.005)
overall sustainability index	0.006	-0.011*
	(0.012)	(0.006)

*Note: *p<0.1; **p<0.05; ***p<0.01*

Table 21: Average Treatment Effect on the Treated (ATT) of rainwater harvesting and fertilizer micro-dosing adoption in yield of maize of Morogoro, 2016 - 2013

	Dependent variable:	
	maize_kg_ha_diff	
	Data before matching	Data after matching
ATT	195.168*	199.047*
	(101.870)	(109.645)
Constant	-310.981***	-281.033***
	(42.959)	(48.806)
Observations	388	323
R^2	0.009	0.010
Adjusted R^2	0.007	0.007
Residual Std. Error	767.276 (df = 386)	785.466 (df = 321)
F Statistic	3.670* (df = 1; 386)	3.296* (df = 1; 321)

*Note: *p<0.1; **p<0.05; ***p<0.01*