World Development 183 (2024) 106732

Contents lists available at ScienceDirect

World Development

journal homepage: www.elsevier.com/locate/worlddev

Regular Research Article

Linking innovations adoption with farm sustainability: Empirical evidence from rainwater harvesting and fertilizer micro-dosing in Tanzania

Diana Escobar Jaramillo [a,b], Linda Arata [a], Kai Mausch [c], Paolo Sckokai [a], Anja Fasse [d,e], Jens Rommel [b], Pierre Chopin [f,g,*]

[a] Department of Agricultural and Food Economics, Università Cattolica del Sacro Cuore, Italy
[b] Department of Economics, Swedish University of Agricultural Sciences, 75651 Ultuna, Uppsala, Sweden
[c] Center for International Forestry Research – World Agroforestry (CIFOR-ICRAF), Nairobi, Kenya and Bonn, Germany
[d] Environmental and Development Economics, Weihenstephan-Triesdorf University of Applied Sciences, Germany
[e] TUM Campus Straubing of Biotechnology and Sustainability; TUM School of Management, Germany
[f] Department of Crop Production Ecology, Swedish University of Agricultural Sciences, 75651 Ultuna, Uppsala, Sweden
[g] Environmental Geography Group, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam 1081HV, the Netherlands

ARTICLE INFO

Keywords:
Food security
Technology adoption
Sustainability indicators
Difference-in-differences
Propensity score matching
East Africa
Impact assessment
Sustainable intensification

ABSTRACT

Food insecurity and poverty are of major concern for farmers and rural households in Tanzania. Innovations to increase the sustainability of households must be carefully investigated by integrating, in the analysis, the effect on crop yields with a holistic view on the overall sustainability and its components. Rainwater harvesting and fertilizer micro-dosing can increase food security, particularly in water-limited contexts, but they can also significantly increase labor requirements and the availability and use of water resources in villages and watersheds. The purpose of this study was to quantify the impacts of rainwater harvesting and fertilizer micro-dosing on environmental, social and economic sustainability of households in two regions in Tanzania – semi-arid Dodoma and semi-humid Morogoro. We selected and calculated 40 sustainability indicators for 892 households in 2013 and 2016, and we applied Difference-in-Difference Propensity Score Matching to identify relative changes in household sustainability. We show that in the dry region of Dodoma, economic sustainability increased less for adopters of the innovations in comparison to non-adopters between the years 2013 and 2016, with 6 percentage points and 11 percentage points respectively. In contrast, in the humid region, the adoption of innovations increased food security by 14 percentage points compared to 6 percentage points in the case of non-adoption. These results highlight that innovations must fit the context and should not be scaled without prior analysis of multiple impact dimensions as they may trigger significant trade-offs. By moving the focus from field to farm scale, this study contributes to providing a more rigorous assessment of the spillover effects that in-field innovations can have on the overall sustainability of households, which is a prerequisite for the advancement of sustainable intensification of agricultural production in the region.

1. Introduction

Food insecurity and poverty are a persistent concern in Sub-Saharan Africa, and access to, as well as the adoption of, technologies for farming remain a challenge. Even basic cultivation technologies with minimal investments can contribute to significant improvements in production and food security (Pan et al., 2018). In Tanzania, only 14 % of the cropped area is mechanically cultivated, and almost all agricultural land

* Corresponding author at: Environmental Geography Group, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam 1081HV, the Netherlands.

E-mail addresses: diana.escobar@unicatt.it (D. Escobar Jaramillo), linda.arata@unicatt.it (L. Arata), k.mausch@cifor-icraf.org (K. Mausch), paolo.sckokai@unicatt.it (P. Sckokai), anja.fasse@hswt.de (A. Fasse), jens.rommel@slu.se (J. Rommel), p.g.b.chopin@vu.nl (P. Chopin).

https://doi.org/10.1016/j.worlddev.2024.106732
Accepted 18 July 2024
Available online 2 August 2024

is rain-fed (Mrema et al., 2020). Easy-to-implement rainwater harvesting[1] combined with fertilizer micro-dosing[2] are considered best practices to address low crop productivity (Biazin et al., 2012; Saidia et al., 2019b), and thus, their dissemination has been recommended over the past decade (Mwinuka et al., 2017; Vanlauwe et al., 2010). This combination of water retention techniques with micro-fertilization has been shown to improve productivity and efficiency in other farming systems (Zhang et al., 2023). In addition, these techniques require little training but can lead to significant time investment which can have spillover effects on the dedication to other farm or household related activities. Genuine sustainability assessment, with a careful selection of indicators can help to capture techniques and innovation effects on many sustainability dimensions such as food security, environmental degradation and income generation, both in the short run and in the long run (Lee, 2005).

Improved water retention and fertilization have proved to increase crop yields, water-use efficiency, and nutrient-use efficiency in soils (Chilagane et al., 2020). Hence, they can potentially improve food security and soil fertility and reduce poverty (Habtemariam et al., 2019). On the other hand, tied ridges used for rainwater harvesting may also lead to water logging in periods of heavy rainfall (Biazin et al., 2012). The broader impacts of these technologies on economic, social and environmental sustainability are, hence, a major concern. Impact assessment studies have generally focused on narrowly defined outcomes at household level related to productivity (e.g., marketed surplus, value of agricultural production and total income, welfare, social capital or information (Bachke, 2019; Faltermeier & Abdulai, 2009; Khonje et al., 2015; Nakano et al., 2018)). For rainwater-harvesting and fertilizer micro-dosing, Schindler et al. (2016) performed an ex-ante assessment of the impact of such technologies and reported the interest of farmers for these two innovations, but they have not captured the real impact of their adoption. An ex-post assessment study has shown the positive impacts of these two technologies for food security and economic profit in Tanzania (Habtemariam et al., 2019) but without capturing the multiple dimensions impacted by their implementation such as the use of labor at farm level or the water efficiency.

The objective of this paper is to evaluate the impacts of new agricultural technologies on a broad set of sustainability indicators at household level. To do so, the sustainable livelihood approach (Carney, 1998) proposes an ensemble of variables that represent households' assets which can be considered as direct drivers of adoption of technologies. Departing from this framework, we develop indicators capturing the impact of the adoption of rainwater harvesting and fertilizer micro-dosing among farm households in Tanzania on the three pillars of sustainability which are independent from the household's assets in terms of calculation. Hence, we add to the scarce literature that provides rigorous impact assessments of these technologies in Eastern Africa. In addition, we focus on the heterogeneous impacts of the adoption of new technologies by contrasting two regions in Tanzania that differ in their biophysical conditions – Dodoma and Morogoro.

The remainder of this paper is structured as follows. In section 2, we provide a short overview of the literature on sustainability impact assessments of technology adoption in agriculture. In section 3, we present and discuss the methods used, namely the calculation of composite sustainability indicators for the three pillars of sustainability and the Propensity Score Matching Difference-in-Differences (PSM-DID) approach. In sections 4 and 5, we present the data and results. We discuss our findings and conclude in sections 6 and 7.

2. Overview on farm sustainability studies and innovations

The impact of innovations on sustainability has been addressed in ex-post assessment using a limited number of sustainability indicators. When assessing technologies adopted in-fields, the agricultural economics literature focuses on capturing the variation of productivity at field level and the potential spill-over effects on income or food security at household level. Such studies primarily address the ability of improved varieties for staple crops, like rice, cowpea or wheat (Manda et al., 2020; Mishra et al., 2016; Nguyen Chau & Scrimgeour, 2021; Shiferaw et al., 2014; Yorobe et al., 2016), or improved animal breeds (Kebebe, 2017) to increase yield and production and subsequently farm revenues, income, and food security at household level, particularly in drought-prone areas. However, impact assessments in these resource-scarce environments call for not only addressing productivity, economic, and food security aspects but also for addressing key environmental processes sustaining agricultural and economic activities in a stronger sustainability perspective (Tittonell, 2014).

The rationale behind these multi-criteria assessments is to estimate both socioeconomic and environmental processes by using a set of relevant indicators (Binder et al., 2010) calculated from large databases (e.g., Ryan et al., 2016) or surveys among farmers (e.g., Felice et al., 2012). The multidimensional nature of farm household systems makes judging sustainability with just one absolute indicator difficult (Hansen, 1996; Moeller et al., 2014). To tackle this limitation, research on farm or household sustainability has rather adopted comparative approaches where the relative sustainability levels of farms are compared among a large population to select the ones that depict a higher level of sustainability and identify the factors or characteristics explaining such levels (Mutyasira et al., 2018). In the same way, before-after comparisons or short-to-long term monitoring of sustainability have been implemented to observe the direction of change of a system towards greater or lower level of relative sustainability (Acosta-Alba et al., 2019). Those comparative approaches in large populations offer the possibility to identify not only incremental management change but more systemic change across a population which can have implications beyond the primarily targeted issues (Chopin et al., 2021).

Soil degradation and food insecurity in Sub-Saharan Africa require responses beyond variety choice, and, in this regard, soil management, including fertilizer micro-dosing and water conservation techniques such as rainwater harvesting are considered a cornerstone of sustainable intensification (Dile et al., 2013; Kuyah et al., 2021). Fertilizer micro-dosing was found to increase yields of millet, sorghum and maize by 68 % on average in Sub-Saharan Africa (Ouedraogo et al., 2020). For rainwater harvesting, positive outcomes in terms of yield, food security and household income were found (Dile et al., 2013), with the latter increasing on average by 62 % in Pakistan, and 38 % in the Tigray region in Ethiopia (Kassie et al., 2008). Combinations of these soil and water conservation technologies showed a synergistic effect and simultaneously tackled low agricultural productivity (Marenya et al., 2020; Aune & Bationo, 2008; Chilagane et al., 2020; Chimweta et al., 2018; Mashingaidze et al., 2013; Ouedraogo et al., 2020; Sanginga & Woomer, 2009) and poverty issues (Mwinuka et al., 2017).

Despite the mentioned increases in productivity, income and food security, water retention may not be beneficial for all agro-ecological conditions and associated off-site effects such as change in water dynamics in the landscape may not have been properly captured (Kassie et al., 2011). In the same way, fertilizer micro dosing enhances yields but may exacerbate nutrient mining leading to soil degradation in the long run (Tovihoudji et al., 2017). Hence, impact studies at household level should assess the impact of the combined use of rainwater harvesting and fertilizer micro-dosing to capture the overall expected benefits on water and soil conservation as found in on station/on-field experiments in contrasted regions in Sub-Saharan Africa.

Contrasted biophysical characteristics affect the overall impact of innovation (Renner et al., 2021), and the level of rainfall drives the

[1] 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 its flow within rows (Germer et al., 2021).

[2] 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 (Tovihoudji et al., 2017).

heterogeneous impacts of soil and water conservation techniques. Ouedraogo et al. (2020) found an 80 % yield increase with fertilizer micro-dosing in Sub-Saharan Africa when the amount of rainfall is above 600 mm/year, but this increase is limited to 51 % in plots with lower rainfall levels. In Niger, a study of 276 farmers' fields indicated no impact of fertilizer micro-dosing on profitability in 34 % of farms due to rainfall heterogeneity (Bielders & Gérard, 2014). In contrast, Kassie et al. (2008) found benefits of soil conservation techniques in Ethiopia only in low rainfall areas in Tigray with an increase in benefits of 59 USD per ha, whilst no effect was found in Amhara which has a three times higher level of rainfall. When soil and water conservation are combined, the impacts can become even more heterogeneous, depending on the distribution of rainfalls and effects arising from levels of rainfall which can account for as much as 92 % of yield differences (Marenya et al., 2020). Taking this into consideration is imperative, since fertilizer micro-dosing and rainwater harvesting target risk-averse smallholder farmers for whom these techniques provide an opportunity to transition to more viable systems (Ruzzante et al., 2021).

Finally, ex-ante impact assessments of sustainability intensification options in Tanzania have been conducted on various technological options, including rainwater harvesting and fertilizer micro-dosing. The ex-ante impact assessment of Graef et al. (2017) indicates that rainwater harvesting and fertilizer micro-dosing are expected to have a higher impact in the semi-arid region and improve food diversity, social relations and working conditions. However, such assessments also show farmers' concern regarding access to inputs required when adopting these technologies. Among these are the risk of a lack of rain and chemical fertilizer that would further decrease yield and the increased workload to construct the infiltration pits that, with limited labor availability, would reduce the field sizes that farmers can cultivate (Schindler et al., 2016). Ex-post assessments controlling for the heterogeneity of farmers' conditions conducted under contrasting climatic conditions will shed light on the synergies or trade-offs that the combined adoption of rainwater harvesting and fertilizer micro-dosing can trigger at household level.

In this study, we analyze the combined effect of rainwater harvesting and fertilizer micro dosing adoption, in order to capture changes in economic, social and environmental sustainability in two contrasted regions in Tanzania. Concerns regarding the ability to draw causal inferences on the impacts of projects from datasets that are not carefully constructed motivate the need to deal with the selection bias (Duflo et al., 2007) and have also been discussed in the context of impact evaluations of agricultural projects in developing countries (Winters et al., 2011; World Bank, 2011). We apply the PSM-DID approach to perform our ex-post assessment which corrects for differences in the observed and time-invariant unobserved characteristics between the households that do adopt the innovation and the households that do not adopt.

3. Sustainability framing and analysis

3.1. Sustainability indicators and composite indices

The database used for this study comprises household characteristics related to financial, physical, natural, human, and social capital for the years 2013 and 2016. This data was used to compute 33 household sustainability indicators which were in turn used to compute twelve sustainability components. The sustainability components have been then aggregated to obtain three composite indices, one for each pillar of sustainability (environmental, economic and social) and one composite index for the overall sustainability. The three indexes provide a complete overview of sustainability at household level.

Our sustainability indicators capture the functioning of the farming systems and their relationships with the households and their external environment. The sustainability assessment follows the method described in Ulukan et al. (2022). The indicators refer to the economic, social, and environmental pillars of sustainability, adopting the global vision of most sustainability measurements (Chopin et al., 2021; Haileslassie et al., 2016; Mutyasira et al., 2018; Silvestri et al., 2022; Yegbemey et al., 2014). Table 1 presents 33 indicators grouped along 12 core components within each of the three pillars of sustainability. The indicators were selected based on relevant literature and data availability, while the 12 components were defined according to site-specific features following the process proposed by ul Haq and Boz (2018).

The components of environmental sustainability are soil management, water management, and agro-diversity, which represent important environmental resources and processes linked to the delivery of ecosystem services in agriculture. Sustainable water use is necessary to mitigate climate change and adapt to a changing climate (Labeyrie et al., 2021; Smith et al., 2008). Water use efficiency measures the ability of farmers to produce fresh products based on their crop choices and the average amount of precipitation they receive in both sites.[3] In the survey, farmers were asked about the litres of water used by the farm-household and the uses of water for which they experienced conflicts. Using this basic data, we computed the share of water for which farmers experienced conflict over total water used by the farm-household. This indicator is not an objective assessment of the level of conflict over water, but rather reflects the subjective experience of the water user (farmer) and their assessment of conflict.

Economic sustainability is composed of profitability, stability and resilience, aiming at the generation of value (Rockström et al., 2017; Rondhi et al., 2018) and the ability to respond to changes in the environment (Lamichhane et al., 2020). Particularly, the indicator high income fluctuation was obtained by asking a categorical question to farmers in which they could choose how much their income fluctuated in the last 3 years (not at all/yes, a bit/yes, a lot). Assets considered in this indicator were: the cash kept at home, livestock, money in the bank account, household durable assets. The households also reported their savings. Subjective evaluation of the shock by the respective household was measured on the scale: 1 = no impact to 4 = high impact.

Social sustainability within an agricultural social system implies fulfilling the needs of the system's actors without compromising the needs of future generations, thus its components include health, wellbeing, social capital, land security and food security (Janker et al., 2019). Some of those social indicators can be considered as drivers of adoption but in our case we consider that the adoption of innovations can triggers a change in way farmers exchange among each other and the contribute to reinforce their resilience. In the case of wellbeing, we used a direct question on the subjective wellbeing. If the household perceived a deterioration, the respondent was asked to rate the severity on the scale: 1 = not at all, 2 = yes, a bit, 3 = a lot.

Table 1 also presents information of the indicators' influence in the sustainability component as "Additive" (i.e. an increase in the indicator leads to an increase in the component) or "Subtractive" (i.e. an increase in the indicator leads to a decrease in the component). The number of missing values for the indicators were 95 out of 41,924 (0.22 %) in 2013 and 12 out of 34,062 (0.04 %) in 2016 due to unanswered questions in the survey. Instead of removing the household for which one of the indicators could not be calculated, we used the function imputePCA from the missMDA package on R. This function predicts missing values with a regression model based on complete observations.

To compute the composite index for one pillar of sustainability, we produced one index for each component of the pillar (second column of

[3] Water indicators benefited from rainfall data collected on a daily basis, using the standard rain-gauges installed at Ilakala and Changarawe study sites for more precise assessment.

Table 1
Description of sustainability indicators with their associated component and pillar.

Pillar	Component	Indicator	Units	Direction	Reference
Environmental	Soil management	Quantity of applied fertilizer produced off-farm (organic and mineral fertilizer)	Kg / ha	Additive	Mutyasira et al. (2018); Pham and Smith (2013
		Quantity of applied animal manure produced on-farm	Kg / ha	Additive	(Negi et al., 2018))
		Crop area perceived as unfertile	% area	Subtractive	Asminaya et al. (2018); Pham and Smith (2013)
		Crop area with perceived decrease in fertility	% area	Subtractive	Onduru and Du Preez (2008); Pham and Smith (2013)
		Crop area under legume	% area	Additive	Moraine et al. (2017); Mutyasira et al. (2018)
		Crop area with residues left on the field	% area	Additive	Wilkus et al. (2019)
		Area where there is an intent to invest in soil fertility	% area	Additive	Lairez et al. (2020); Thierfelder et al. (2022)
		Average tree density	Number of trees / ha	Additive	Escribano et al. (2018); Yegbemey et al. (2014)
		Area under erosion control measures	% area	Additive	Mutyasira et al. (2018)
	Water management	Presence of irrigation	Yes – No	Subtractive	Özerol et al. (2012)
		Rainfall water use efficiency	Kg / ha / mm of rainfall	Additive	Medrano et al. (2015)
		Change in household water consumption	Liters/day	Subtractive	Abu-Bakar et al. (2021); Vanham and Bidoglio (2013)
		Water use conflict	% of amount	Subtractive	Veisi et al. (2020)
	Agricultural diversity	Tree diversity	Number of species	Additive	Fadul-Pacheco et al. (2013); Gaviglio et al. (2017)
		Crop diversity	Number of species	Additive	Fadul-Pacheco et al. (2013); Gaviglio et al., 2017)
		Livestock diversity	Number of species	Additive	Fadul-Pacheco et al. (2013); Gaviglio et al. (2017)
Economic	Crop profitability	Crop gross margin	USD / ha	Additive	Antunes et al. (2017)
		Crop expenditures	USD / ha	Subtractive	Viteri Salazar et al. (2018)
		Labor productivity	USD / person	Additive	Bernués et al. (2011); Mutyasira et al. (2018)
		Post-harvest loss	% amount	Subtractive	Anriquez et al. (2021); Stathers et al. (2020)
	Profitability	Net household income	USD	Additive	Kansiime et al. (2018)
	Stability	High income fluctuation	Yes – No	Subtractive	ul Haq and Boz (2018)
		Has savings	Yes – No	Additive	Vilei (2011)
	Reduction of vulnerability to shocks	Loss of income due to shock	USD	Subtractive	Baccar et al. (2019); Lien et al. (2007)
		High severity of shock	Yes – No	Subtractive	Baccar et al. (2019); Lien et al. (2007)
		Time to recover after shock	Number of months	Subtractive	Muricho et al. (2019); Rao and Rogers (2006)
Social	Food security	Potential Food Availability index (PFAI)[1]	Ratio	Additive	Lopez-Ridaura et al. (2018)
		Months of inadequate food provisioning	Number of months	Subtractive	Jones et al. (2013)
		Food Consumption Score (FCS)[2]	Score	Additive	Kissoly et al. (2017)
		Coping Strategies Index (CSI)[3]	Score	Subtractive	Jones et al., (2013)
	Health	Health insurance binary	Yes – No	Additive	ul Haq and Boz (2018)
		Healthy household members	% of people	Additive	Marandure et al., (2017); ul Haq and Boz (2018)
	Wellbeing	Hours worked	Hours/active household member	Subtractive	Antunes et al. (2017); Firbank et al. (2018)
		Perceived deterioration of household situation	Yes – No	Subtractive	Ripoll-Bosch et al. (2012)
		High impact of income fluctuations on wellbeing	Yes – No	Subtractive	Angelsen and Dokken (2018)
	Social capital	Information network	Number of sources	Additive	Hoang et al. (2006); Pretty et al. (2007)
		% of crops receiving support from farmers group	%	Additive	Mutyasira et al. (2018); Pretty et al. (2007)
	Land security	Land title ownership	% of area	Additive	Shakya et al. (2019)
		Secure land	% of area	Additive	Clover and Eriksen (2009); Shakya et al. (2019)
		Land use conflict	% of area	Subtractive	Shakya et al. (2019)

[1] Potential Food Availability index (PFAI): represents a households' potential food consumption expressed in energy equivalents with respect to its energy needs for a year (Frelat et al., 2015).
[2] Food Consumption Score (FCS): the possible range is between 0 and 112 points and measures a frequency weighted diet diversity index (Wiesmann et al., 2009).
[3] 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 (Maxwell & Caldwell, 2008).

Table 1) by normalizing the indicators, assigning them a weight and aggregating them. Min-max normalization of the indicators is performed (Gómez-Limón & Sanchez-Fernandez, 2010; Haileslassie et al., 2016; Mutyasira et al., 2018) by considering the minimum and the maximum values of that indicator in 2013 and 2016. Before the normalization process, extreme values from outliers were identified using the Grubbs's test and their values were replaced by the values from the closest non-outliers. We use Eq. (1) for additive indicators, and equation (2) for subtractive indicators as follows:

$$Ind\_norm_{i,t} = \frac{Ind_{i,t} - \min(Ind_{\bullet,\bullet})}{\max(Ind_{\bullet,\bullet}) - \min(Ind_{\bullet,\bullet})} \quad (1)$$

$$Ind\_norm_{i,t} = \frac{\max(Ind_{\bullet,\bullet}) - Ind_{i,t}}{\max(Ind_{\bullet,\bullet}) - \min(Ind_{\bullet,\bullet})} \quad (2)$$

where $Ind\_norm_{i,t}$ is the normalized value of an indicator for household i in year t, $Ind_{i,t}$ is the observed value of the indicator, $\min(Ind_{\bullet,\bullet})$ and $\max(Ind_{\bullet,\bullet})$ are the minimum and maximum values of the indicator in the sample, respectively. The resulting value lies between [0, 1], where 0 indicates the least sustainable and 1 the most sustainable observation. Then, a weight is assigned to each normalized indicator such that the sum of the weights over all the indicators entering one component of the pillar of sustainability equals one. All continuous indicators carry the same weight, while binary indicators are given half the weight of continuous indicators, since they provide less information (Chopin et al., 2019).

In this study, stakeholders were not involved in providing their views over the sustainability of farms and the importance of the various indicators. We hence considered that all the indicators could be weighted equally following a first diagnosis conducted in the same region on the sustainability of agricultural systems (Ulukan et al., 2022). For instance, the crop diversity component has three quantitative indicators which all received a weight of 0.33, whilst for the component reduction of vulnerability to shocks the two quantitative indicators Loss of income due to shock and Time to recover after shock had a weight of 0.4, whilst the qualitative indicator High severity of shock (Yes/No) received a weight of 0.2. Lastly, weighted normalized indicators are aggregated to calculate composite indices per component (Eq. (3)):

$$CI_j = \sum_{i=1}^{n} w_i * Ind\_norm_i \quad (3)$$

where CI stands for the composite index j for one component of the pillar of sustainability, n is the number of indicators per composite index, and w is the weight assigned to the constituent indicator i. The three composite indices, one for each pillar of sustainability, and the composite index for overall sustainability, are calculated by simple averages of the components' indices in the first case and the three composite indices in the second case.

3.2. Difference-in-Difference propensity Score matching

To evaluate the impacts of the adoption of the innovations on the sustainability of households in Morogoro and Dodoma, we apply PSM-DID and we estimate the Average Treatment Effect on the Treated (ATT) for each sustainability indicator as well as for the components and the overall index. The adoption of innovations is a voluntary decision, and it is likely that the characteristics of the households that decide to adopt the innovation (in this study water-harvesting and fertilizer microdosing) are different from the characteristics of the ones that do not adopt the innovation, making difficult to understand if a difference in the sustainability is due to households differences or due to innovation adoption. Thus, a naive comparison between adopters and non-adopters may result in biased estimates (Chabé-Ferret, 2015). PSM-DID allows to control for selection bias on observables and unobservables that do not vary over time, and it makes the group of adopters comparable with the group of non-adopters (Heckman et al., 1997).

The first step of PSM-DID is a binary regression over a set of households and environment characteristics to predict the probability of the household to adopt the treatment (i.e. innovation adoption). This probability is called propensity score, and households with similar scores are assumed to be comparable. The household and environment characteristics used as covariates for the binary regression are different variables inspired by the sustainable livelihood approach previously used to describe the resources of households in Tanzania (Ulukan et al., 2022). Human capital encompassed the household structure variables, including education, age and experience. Natural capital was represented by total area managed by the household, proportion of land use types and livestock. Financial capital was described by livelihood strategy variables, such as proportion of cash crops. Physical capital was the pure value of assets from the households and in terms of production. In the second step of the PSM-DID, treated individuals are matched with non-treated individuals based on the propensity score values by a proper matching algorithm (e.g. Caliendo & Kopeinig, 2008). Tests are performed to check whether the matched groups of the treated and untreated individuals are comparable. Finally, in order to assess the effect of the treatment adoption, the ATT is estimated. The ATT in the case of PSM-DID indicates the difference in the outcome change between the treatment adopters and the non-adopters over the period considered. PSM-DID is widely used to evaluate the effect of a farmer's participation in a policy program or of a farmer's adoption of an innovation (Arata & Sckokai, 2016; Dillon, 2011; Mennig & Sauer, 2020; Peralta et al. 2018; Pufahl & Weiss, 2009; Udagawa et al., 2014).

PSM-DID relies on two assumptions. First, the DID mean independence assumption posits that the average outcome of the treated and untreated groups would follow a parallel trend had the treatment not been applied. Second, the common support condition posits that for each unit, there potentially exists at least one other unit to match with.

In our analysis, we apply a logistic regression, and we perform all the steps of the PSM-DID separately for Dodoma and Morogoro, due to the differences between their biophysical characteristics. Our treated group in a region is composed by the sample households that adopted the rainwater harvesting and fertilizer micro-dosing after 2013 (our initial year), while our untreated group in a region is composed by the sample households that had never adopted the coupled innovations or one or the other over the time span 2013–2016. The covariates that enter the logistic regression are chosen based on literature and expert consultations. They include socio-demographic characteristics such as the age and educational level of household head and key variables about the farming systems summarized via proportion of crop categories in the total cultivated area of each household. We apply the nearest neighbor matching algorithm with replacement, with 10 neighbors and caliper of 0.1 (Caliendo & Kopeinig, 2008). The caliper limits the possible matching units based on the distances between propensity scores. There is no common rule on the caliper to adopt. Based on literature that uses calipers between 0.5 and 0.1 (Becerril & Abdulai, 2010; Arata & Sckokai, 2016; Mennig & Sauer, 2020), we applied a 0.1 caliper. We also impose the common support condition by defining the region of common support as the region where there is overlap between the treatment and the control groups' propensity scores. Figs. A3 and A4 present the distribution of propensity scores among treated and untreated units, allowing the visualization of their overlapping range.

The estimate of the ATT in our analysis is defined as follows:

$$DID = \frac{1}{N}\sum_{i=1}^{I\cap S}\Big[\Big(Ind\_norm^{1}_{i,2016} - Ind\_norm^{0}_{i,2013}|D=1\Big) - \sum_{v=1}^{V\cap S} weight_{iv}(Ind\_norm^{0}_{v,2016} - Ind\_norm^{0}_{v,2013}|D=0)\Big] \quad (4)$$

where N is the number of households that adopt the innovations, V is the number of matched households that have never adopted the innovation in the time span 2013–2016, D takes value of 1 for adopters and 0 for non-adopters, S indicates the common support, $weight_{iv}$ indicates the weights that range between [0, 1]. Hence, DID in our analysis indicates the difference in the average change between 2013 and 2016 in each sustainability indicator between the households that adopt the two innovations (rainwater harvesting and fertilizer micro-dosing) and the similar households that have never adopted them.

Table 2
Summary of the environmental and agricultural characteristics of Morogoro and Dodoma regions (Sources: Graef et al., 2014).

Characteristics		Morogoro	Dodoma
Biophysical	Climate	Semi-humid	Semi-arid
	Precipitation	600–800 mm per year	350–500 mm per year
	Temperature	Annual average of 25 °C; 18 °C to 30 °C in the lowlands	Annual average of 22 °C; 14 °C to 30 °C
	Topography	Flat plains, highlands, and dry alluvial valleys	Flat plains and small hills
Socio-economic	Food security	Different levels of food insecurity	Predominantly low food security
Agricultural	Major crops for household consumption	Maize, rice, sorghum, legumes, horticulture	Sorghum, millet, maize
	Major cash crops	Sesame, sunflower, sugarcane, cotton, sisal	Sesame, groundnuts, sunflower
	Livestock	Poultry, cattle, goats. Secondary source of income	Poultry, cattle, sheep, goats. Main source of income

4. Data

4.1. The dataset

The data were collected through a survey conducted in Tanzania as part of a large trans- and interdisciplinary research project.[4] The two regions were chosen because they represent the large variability of farming systems in the region, differing for example by market access and rainfed cropping systems, with the objective of integrating livestock and village sizes with 800–1500 households. Furthermore, the selection of these technologies to be introduced in the locations studied was done together with village authorities and farmers to be tailored to the households' needs, expecting to face the challenge of economic accessibility, which caused small share of farmers using fertilizers, particularly chemical ones. In each region, 3 villages were selected and within each village 150 households were randomly sampled from household lists provided by the village head. Within each region, 1 village was selected as a control site while the other 2 were intervention sites (Brüssow et al., 2017). Between the two survey waves, about 5 % of households dropped out (migration, not found anymore, death).

The project used participatory research methods to evaluate and promote a combination of rainwater harvesting and fertilizer micro-dosing to improve food security. The project implemented a mother-baby trial design where demonstration (mother) plots were set up to facilitate learning and supported farmers to test the technology on their own farms (baby plots). The mother plots were set up and managed by the regional centers of the Tanzanian national agricultural research institutes. These acted as learning sites and farmers were exposed to the technology there. Volunteer farmers were then supported to implement the approach in their own fields (baby plots).

The technology packages that were introduced combine water harvesting approaches with fertilizer micro dosing (for details see Saidia et al., 2019b, 2019a). For the demonstration plots, the recommended rate (40 kg P/ha and 80 kg N/ha for maize, 20 kg P/ha and 18 kg N/ha for pigeon-pea) and a control of no fertilizer was compared to the micro dosing (10 kg P and 20 kg N/ha in maize; 10 kg P and 9 kg N/ha in pigeon-pea). In addition, tied ridges were introduced to improve water use. Ridges were 75 cm apart and 20 cm high and 15 cm high ties were 150 cm apart. Fertilizer (DAP and urea) were added in holes 5 cm away from plant hills. 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, and because both regions represent a majority (between 70 and 80 %) of the farming system types found in the country (Graef et al., 2014). Table 2 presents a comparison of the two regions' characteristics. While Morogoro is a semi-humid region with flat plains, highlands, and dry alluvial valleys, Dodoma is a semi-arid region with flat plains and small hills.

The data has a panel structure with 448 observations for the region of Dodoma and 444 for the region of Morogoro in the baseline year 2013, before the project started its interventions, and 420 observations for Dodoma and 391 for Morogoro in the year 2016, when the project had been implemented. In 2016, 26 % of the sample households from Dodoma and 18 % of the sampled households from Morogoro were adopters of both innovations (See Table A10). Farmers were encouraged to adopt both innovations due to their synergistic effects. Thus, in this study it is not possible to explore the individual effect of each innovation.

4.2. Household characteristics

In Dodoma and Morogoro, the average family size is five people, and the household head is 50 years old on average. The average experience in agriculture in Dodoma is higher than in Morogoro – 20 years versus 16 years in 2016 – while in both regions the average time spent on education is four years. The land managed by each household is around 2.5 ha in both regions, and in the year 2016, an average of 80 % of it was used for cropping. 40 % of the active members worked off-farm in Dodoma in 2016, while in Morogoro this percentage was 30 %. The hours worked per hectare increased from the year 2013 to the year 2016 in Dodoma and Morogoro, reaching about 650 and 700 h, respectively. The area perceived as fertile increased in both regions, doubling in Dodoma from 30 to 60 % and increasing in Morogoro from 50 % to 60 %. While the percentage of farms affected by drought decreased by 20 percentage points in Dodoma, in Morogoro this number increased by the same percentage. The proportion of households that cultivate cash crops in Dodoma doubled in the year 2016 to 20 % as well as the share of farmland allocated to maize, while in Morogoro the maize land share decreased to 40 %. The expenditure on fertilizers and pesticides more than doubled between 2013 and 2016 in Dodoma and it reached 8.3 USD per hectare, while in Morogoro it remained stable at around 12 USD per hectare. The value of productive assets owned by the households was on average 75 USD in Dodoma, while in Morogoro it doubled from the year 2013 to the year 2016, reaching almost 64 USD. Tables A1 and A2 in Online Appendix 1 present more details and summary statistics.

5. Results

5.1. Sustainability indicators

Table 3 presents the summary statistics of the sustainability indicators for the two regions in 2013 and 2016, together with the results of a simple test for difference between means over the two periods. As mentioned in the methods section, we have chosen to use nearest neighbor matching algorithm with replacement, with 10 neighbors and a caliper of 0.1, however we have also tested the results by changing the

[4] 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: https://www.*trans*-sec.org/.

Table 3
Summary statistics of indicators for components and composite indices for Dodoma and Morogoro.

	Dodoma 2013 (n = 448)		Dodoma 2016 (n = 420)		Difference Dodoma 2016 – 2013	Morogoro 2013 (n = 444)		Morogoro 2016 (n = 391)		Difference Morogoro 2016 – 2013
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Soil management	0.36	0.12	0.33	0.11	−0.03***	0.3	0.09	0.32	0.1	0.02***
Water management	0.55	0.11	0.62	0.12	0.07***	0.6	0.09	0.59	0.12	−0.01
Agricultural diversity	0.24	0.14	0.24	0.12	0.00	0.17	0.11	0.25	0.11	0.08***
Crop performance	0.55	0.09	0.55	0.09	0.00	0.63	0.13	0.54	0.12	−0.09***
Profitability	0.22	0.25	0.28	0.25	0.06***	0.29	0.29	0.32	0.28	0.03
Stability	0.35	0.34	0.65	0.35	0.3***	0.55	0.33	0.57	0.34	0.02
Reduction of vulnerability to shocks	0.7	0.19	0.75	0.15	0.05***	0.85	0.19	0.73	0.17	−0.12***
Food security	0.43	0.15	0.54	0.15	0.11***	0.53	0.17	0.58	0.14	0.05***
Health	0.66	0.21	0.65	0.23	−0.01	0.63	0.2	0.63	0.23	0.00
Wellbeing	0.62	0.24	0.64	0.23	0.02	0.77	0.2	0.6	0.24	−0.17***
Social capital	0.24	0.24	0.13	0.13	−0.11***	0.12	0.15	0.1	0.13	−0.02**
Land security	0.48	0.19	0.5	0.2	0.02	0.39	0.18	0.43	0.2	0.04***
Environmental index	0.38	0.08	0.4	0.07	0.02*	0.36	0.06	0.39	0.07	0.03***
Economic index	0.46	0.12	0.56	0.13	0.1***	0.58	0.15	0.54	0.14	−0.04***
Social index	0.49	0.1	0.49	0.1	0.00	0.49	0.08	0.47	0.1	−0.02***
Overall index	0.44	0.07	0.48	0.08	0.04***	0.48	0.07	0.47	0.08	−0.01**

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

number of neighbors.[5]

The overall sustainability index for Dodoma increased significantly driven by the rise in the economic index (Table 3). In Dodoma, there is a significant increase in the component indicators of the economic index for profitability, stability, and reduction of vulnerability to shocks. The composite environmental index did not change significantly between 2013 and 2016 in Dodoma: the decrease in the indicator for soil management offsets the increase in the indicator for water management. Likewise, the composite social index for Dodoma had no significant change; the increase in the indicator for food security compensates for the decrease of the social capital indicator.

For Morogoro, the overall sustainability index decreased between 2013 and 2016 (Table 3). The index for the economic sustainability as well as its components of crop performance and reduction of vulnerability to shocks had a significant decrease. 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 management indicator and no significant change in the water management indicator, while the diversity indicator increased significantly between 2013 and 2016. The composite index for social sustainability had a significant decrease. This fall is caused by a significant decrease in wellbeing and social capital, although there was a significant increase in food security and land security. Disaggregated data about the sustainability indicators is shown in Online Appendix 1, Tables A3 and A4.

5.2. Characteristics associated with the adoption of the innovations

The drivers of adoption of the two innovations seem to differ in Morogoro compared to Dodoma (Table A9 in the Online Appendix). In Morogoro a better level of education of the household head as well as a higher land security index increases the probability of uptake for the two innovations, while in Dodoma this probability increases for households with a higher value of production assets and decreases with an increase in the share of land allocated to cash crops.

The goal of any matching procedure is to make the treated group comparable with the non-treated group such that any difference between them can be ascribed to the effect of the treatment. In our datasets, most of the observed characteristics of the households used in the matching does not show any statistically differences between the treated and untreated groups in the pre-treatment year (2013) even before the matching (Tables A5 and A7). The only exceptions are represented by the share of cropped area dedicated to cash crops in Dodoma and the education of household head and the land security index in Morogoro, which are all balanced before the matching only if we consider a significance level of 90 %. In order to remove these slight differences between the treated and the untreated groups, we decide to apply the matching and we present the results of the treatment effect without the matching in Table A11 of the Appendix. We perform some diagnostic tools to check whether the matching procedure can create a control sample similar to the treated sample in each region. Specifically, we applied a *t*-test on the mean differences between the treated and the control group, the standardised mean differences and the variance ratio (Tables A5−A8 and Figs. A1 and A2). The *t*-test shows that the mean of the two samples is balanced in both regions after the matching and the standardised mean difference is strongly reduced after matching in both regions. The variance ratio shows values for Dodoma (from 0.81 and 1.23) that are close to the desirable range of 0.92–1.08 (Austin, 2009). In the case of Morogoro, some values are not close to the range, which indicates the lack of a good overlap between the variable probability distributions in the two groups in the region. However, taking the three diagnostic tools together we can conclude that also in Morogoro the two groups are comparable.

5.3. Impacts of the innovations on the sustainability of households

The estimated impacts of adopting rainwater harvesting and fertilizer micro-dosing across the economic, social and environmental aspects

[5] The study acknowledges the sensitivity of its results to variations in the number of nearest neighbors used for matching, as indicated by robustness tests employing 1:1 and 1:5 nearest neighbor matching. However, the primary objective of the paper is to assess the differential impacts of innovations, specifically rainwater harvesting and fertilizer microdosing, on the three sustainability pillars, considering geographical and demographic characteristics. Overall, the study concludes that these innovations affect sustainability components differently in semi-arid Dodoma and semi-humid Morogoro. In Dodoma, there's a decrease in the "quantity of fertilizer applied" indicator under all three estimations, while Morogoro shows consistent improvements in social pillar indices across all estimations tested, particularly in Coping Strategies and food security.

Table 4
Average treatment effect on the treated (ATT) of rainwater harvesting and fertilizer micro-dosing adoption in Dodoma and Morogoro, 2013–2016 (After matching algorithm applied).

Sustainability pillar	Outcome variable:	Units	Dodoma				Morogoro			
			ATT	SD	Difference between mean values 2016–2013 of Matched Control Group	SD	**ATT**	SD	Difference between mean values 2016–2013 of Matched Control Group	SD
Environmental	Quantity of applied fertilizer produced outside the farm	Kg / ha	**−966.3***	(505.1)	951.54***	(342.56)	**−456.4**	(386.5)	456.6	(312.76)
	Quantity of applied animal manure produced inside the farm	Kg / ha	**2.83**	(133.3)	−48.76	(58.83)	**−10.82**	(54.98)	−34.23	(26.97)
	Presence of irrigation	Yes – No	**−0.01**	(0.02)	0.00	(0.01)	**0.00**	(0.04)	0.04**	(0.02)
	Rainfall water use efficiency	Kg / ha / mm of rainfall	**0.11**	(0.08)	0.59***	(0.04)	**−0.07**	(0.08)	0.51***	(0.04)
	Change in household Water consumption	Liters / day	**−35.8***	(20.58)	−20.30**	(9.37)	**−14.03**	(12.63)	−5.9	(4.88)
	Water use conflict	% of amount	**0.05**	(0.03)	−0.11***	(0.02)	**0.01**	(0.04)	−0.02	(0.02)
	Soil management index	0 to 1	**−0.01**	(0.02)	−0.03***	(0.01)	**0.01**	(0.02)	0.01	(0.01)
	Water management index	0 to 1	**−0.01**	(0.02)	0.07***	(0.01)	**−0.01**	(0.02)	−0.00	(0.01)
	Agricultural diversity index	0 to 1	**−0.02**	(0.02)	0.00	(0.01)	**0.05****	(0.02)	0.05***	(0.01)
	Environmental Sustainability index	0 to 1	**−0.02**	(0.01)	0.01**	(0.01)	**0.02**	(0.01)	0.02***	(0.01)
Economic	Crop gross margin per ha	USD / ha	**−6.72**	(42.41)	67.39***	(21.77)	**5.60**	(138.3)	−226.23***	(73.06.90)
	Crop expenditures per ha	USD / ha	**12.69**	(15.81)	17.90**	(7.14)	**40.58**	(60.74)	18.56	(57.54)
	Labor productivity	USD / person	**0.03**	(0.12)	−0.02	(0.06)	**0.31**	(0.26)	−0.57***	(0.14)
	Post-harvest loss	% amount	**−2.03**	(1.31)	−0.04	(0.61)	**0.29**	(1.11)	1.49***	(0.54)
	Net household income	USD	**−40.05**	(200.1)	1,409.98***	(110.01)	**−118**	(195.9)	1,437.05***	(96.49)
	High income fluctuation	Yes – No	**0.06**	(0.09)	−0.06	(0.04)	**−0.04**	(0.09)	0.40***	(0.04)
	Has savings	Yes – No	**0.09**	(0.06)	0.60***	(0.03)	**0.08**	(0.09)	0.27***	(0.04)
	Loss of income due to shock	USD	**110.6**	(147.4)	54.31	(59.80)	**282.9**	(203.7)	571.16***	(68.27)
	High severity of shock	Yes – No	**0.04**	(0.07)	−0.04	(0.04)	**0.06**	(0.09)	0.40***	(0.04)
	Months to recover after shock	Number of months	**−1.67**	(5.79)	−13.59***	(3.17)	**16.63**	(51.43)	25.29	(17.84)
	Crop profitability index	0 to 1	**−0.01**	(0.02)	0.01	(0.01)	**0.02**	(0.03)	−0.09***	(0.01)
	Profitability index	0 to 1	**−0.05**	(0.04)	0.07***	(0.02)	**0.04**	(0.07)	0.03	(0.02)
	Stability index	0 to 1	**−0.1***	(0.06)	0.31***	(0.03)	**−0.08**	(0.07)	−0.01	(0.03)
	Vulnerability to shocks reduction index	0 to 1	**−0.03**	(0.03)	0.06***	(0.01)	**0.03**	(0.04)	−0.14***	(0.02)
	Economic sustainability index	0 to 1	**−0.05****	(0.02)	0.11***	(0.01)	**0.00**	(0.03)	−0.05***	(0.01)
Social	Potential Food Availability index (PFAI)	Kcal produced & purchased / Kcal needs / household / year	**0.03**	(0.27)	0.04	(0.18)	**0.08**	(0.31)	0.08	(0.13)
	Months of inadequate food provisioning	Number of months	**−0.29**	(0.59)	−0.79**	(0.31)	**−1.43***	(0.84)	−0.87**	(0.35)
	Food Consumption Score (FCS)	From 0 to 112	**−0.16**	(2.67)	0.56	(1.27)	**3.86**	(3.2)	0.59	(1.27)
	Coping Strategies Index (CSI)	Score for frequency and severity of	**6.31***	(3.42)	−30.80***	(1.90)	**−14.04*****	(4.99)	−4.27**	(1.81)

(continued on next page)

Table 4 (*continued*)

Sustainability pillar	Outcome variable:	Units	Dodoma				Morogoro			
			ATT	SD	Difference between mean values 2016–2013 of Matched Control Group	SD	**ATT**	SD	Difference between mean values 2016–2013 of Matched Control Group	SD
		hunger facing measures								
	Food security index	0 to 1	−**0.02**	(0.02)	0.11***	(0.01)	**0.08*** **	(0.03)	0.06***	(0.01)
	Social sustainability index	0 to 1	**0.01**	(0.02)	−0.00	(0.01)	**0.02**	(0.02)	−0.02***	(0.01)
	Overall sustainability index	0 to 1	−**0.02**	(0.01)	0.04***	(0.01)	**0.01**	(0.01)	−0.02***	(0.01)

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

of sustainability of the farming households in Dodoma and Morogoro are presented in Table 4.[6] Although the adoption of the innovations did not result in a significant effect on the overall sustainability index in any of the two regions, some effects were revealed when considering the single components of the index (Table 4). For the humid area of Morogoro, adopting the innovations increased the agricultural diversity index by 5 percentage points compared to the non-adopters. In Morogoro, no effect was observed on the economic side while some effects were revealed for some of the social indicators. Specifically, adopting the innovations led to an increase in the food security index in the case of adopters by 8 percentage points that is significantly larger compared to the 6 percentage points increase for non-adopters. A positive effect was also detected in the period of inadequate food provisioning, which decreased by about 2 months in the treatment group, in comparison to the 0.8 month decrease in the non-treated group. Moreover, adopters experienced a larger decrease in the Coping Strategies Index. This index dropped by 18.31 points for households adopting the innovations compared to a drop of 4.27 points among non-adopters. In the dry region of Dodoma, the adopters experienced some effects in the environmental domain. While in this region, both the adopters and the non-adopters experienced a drop in water use over the time span 2013–2016, the drop for the first was much higher. Indeed, non-adopters decreased their water use by 20 L/day compared to a drop by around 56.1 L/day in adopter households. In addition, while the households that did not adopt the innovations showed an increase in the quantity of fertilizer applied per hectare, the households that did adopt the innovations display a decrease in this indicator.

The economic sustainability indicator of the treated units increased by only 6 percentage points, in comparison to the increase of 11 percentage points for the control units. This is due to the increase of 21 percentage points in the stability index for the households that adopted the treatment, in comparison to the increase of 31 percentage points for the non-adopters. The only social indicator affected in the region of Dodoma was the Coping Strategies Index that decreased by 24.5 points in the treated group, while in the non-treated group it decreased by 30.8 points.

Looking at the differences between the treatment effects reported in Table 4 with the treatment effects obtained without performing any matching (Table A11), most of the results are similar in terms of sign and significance, but some important differences exist. As expected, the simple comparison between the trends of the treated and the untreated groups without matching leads to a higher number of significant effects compared to the results obtained by matching. Specifically, in Dodoma, differences in the water use conflict, the agricultural diversity index, the household savings, the overall sustainability index and in Morogoro the stability index and the Food Consumption Score, are all significant if we do not apply any matching procedure, while they lose significance if we apply it. It is likely that the differences in the trends of these outcomes are not due to the adoption of fertilizer micro-dosing and rainwater harvesting, but rather to the differences in the characteristics of the two groups. The agricultural diversity index in Morogoro and the coping strategy index in Dodoma are the only two outcomes that resulted to be significant when matching is applied and not when matching is not applied.

5.4. Sensitivity analysis on the ATT

The DID-PSM estimator controls for the presence of bias due to observed factors and unobserved factors that are constant over time. Hence, the outcome trends of the treated and the matched control group should be parallel in the absence of treatment. However, there may be unobserved factors that vary over time that simultaneously affect the probability of participating in the treatment and the outcome, which undermine the parallel trend assumption and bias the estimates.

One empirical test that is sometimes applied to check this assumption is called placebo test (Chabé-Ferret & Subervie, 2013) and it consists in estimating the ATT between the two matched groups before the introduction of the treatment, where the parallel trend should hold. This requires observing data for at least one period before the treatment introduction. This requirement makes the placebo test barely applied in the agricultural economics literature in developing countries (Haile et al., 2017; Simonet et al., 2019), where pre-treatment data are usually not available. The theoretical development of the PSM proposes another approach to test the sensitivity of the results to the potential presence of hidden bias, the Rosenbaum (2002, 2007) sensitivity analysis. Differently from the placebo test, the Rosenbaum approach does not detect whether there is hidden bias, but rather how strong hidden bias (indicated by Γ) should be to undermine the statistical significance of the ATT. Γ is defined as the ratio of the probabilities of receiving the treatment between a unit belonging to the treated group and one matched control unit. If Γ is set equal to one, after controlling for the observed factors, the treatment assignment is considered random, i.e. both units have the same probability of receiving the treatment.

As we do not have data for the period before the introduction of

[6] Estimation has been performed by the R package MatchIt and robust standard errors are computed.

innovations, we cannot test the parallel trend assumption, but we do test how sensitive our outcomes are to unobserved factors changing over time (which could undermine the results). The unobserved time invariant factors are controlled for in the DID approach and hence they do not represent a source of hidden bias. We present the sensitivity analysis only for the outcomes with a statistically significant ATT. From Tables A12–A14 in the Appendix one can see that most of the significant ATT lose statistical significance if Γ is between 1.2 and 1.4. This means that if there is an observed factor that varies over time which makes a treated (control) unit 20 %-40 % more likely of receiving the treatment than the corresponding matched control (treated) unit, then the conclusion on the ATT is no longer valid. In Dodoma, the outcomes that are more sensitive to the potential presence of a hidden bias are the stability index and the coping strategies index. Both become statistically insignificant even at 10 % level for $\Gamma = 1.2$. The critical level of Γ at which the conclusions of an impact of the studied program on the quantity of applied fertilizer produced off-farm, the change in household water consumption, and the economic sustainability index is undermined is 1.4. The coping strategies index is the most robust result for Morogoro. Indeed, it is affected by a bias of magnitude equal to 3. The other significant results in Morogoro are impacted by an unobserved factor which affects the ratio of being treated between 20 % and 40 %.

The sensitivity test does not detect the actual presence of hidden bias, but it just indicates how strong the hidden bias must be to undermine the conclusions. In addition, as we combine the PSM with DID, our concern refers only to the unobserved factors that vary over time, since we control for the time-invariant unobserved factors.

6. Discussion

In line with previous studies, our analysis shows that the impacts of innovations are heterogeneous across different dimensions of sustainability, as well as among geographical, biophysical, and other regional conditions. In the semi-humid region of Morogoro, the adoption of innovations improved households' food security but impacts on other social, economic and environmental indicators were small. In the semi-arid region of Dodoma, we found a positive impact on household water consumption, but also a smaller increase in economic sustainability with respect to non-adopters.

Some of the covariates used in the DID-PSM were not balanced before matching. Hence, a simple comparison of adopters and non-adopters would have led to biased treatment effect estimates (see Online Appendix 1 Table A11). For example, adopters of innovations in Dodoma had a lower share of land dedicated to cash crops, lower agricultural diversity and more water use conflicts, but they also had a higher probability to have savings. Although there is a market risk from selling cash crops, they can offset subsistence crop failure (Maxwell & Fernando, 1989). Previous studies also established a link between the adoption of technological innovations in agriculture and land tenure security (Jansen et al., 2006), higher levels of education and food security (Kebede et al. 1990), and higher incomes and knowledge of nutrition (De Cock et al., 2013).

In Morogoro, the increase in food security goes together with an improvement in agricultural diversity. The increase by 5 percentage points of the agricultural diversity index for adopters of fertilizer microdosing may be due to the increase in fertilizer available. As explained by the research of Schindler et al. (2016) farmers assert that the access to fertilizer motivates them to plant crops that they do not cultivate presently. The diversity in agricultural landscape is known to have an indirect positive effect on households' food access because of the provision of ecosystem services that regulate and support crop production (Leroux et al., 2022). Similarly, previous research showed improved food security by diversification of crops cultivated after the adoption of rainwater harvesting (Biazin et al., 2012).

We did not find evidence of large or statistically significant increases in economic sustainability in Morogoro even though food security indicators improved. Higher yields might not translate into higher net incomes or an improvement in other economic indicators due to factors implied in the use of innovations, like investment costs and the opportunity cost of family labor that previously worked off-farm (Adolwa et al., 2019). Furthermore, the lack of connection between economic benefits and food security could be explained by commercialization constraints. The commercialization of crops produced is often focused on large farms with high capital (Barrett et al., 2012), which leaves small farms weakly integrated into food markets and dependent for food security on local food production and less on household income (Herrmann et al., 2018). On the other hand, some of the economic benefits of rainwater harvesting may only emerge in the long-run (Ellis-Jones & Tengberg, 2000). Collecting a third survey wave could shed more light on these long-term impacts.

A differentiated impact could emerge from heterogeneity in labor costs. Both studied technologies are labor-intensive. According to some recent estimates, the construction of tied ridges for crop cultivation under water harvesting requires 107.6 h per person per acre, while flat cultivating requires only 24.3 h per person and acre (Germer et al., 2021). In other words, the benefits may be higher in regions with low overall labor costs or low opportunity costs of labor within subsistence farmer households (Habtemariam et al., 2019; Sieber et al., 2018).

In Dodoma, improvements in household food security and income were expected with rainwater harvesting and fertilizer micro-dosing due to its semi-arid climate, according to an ex-ante assessment by Graef et al. (2017). However, we cannot confirm such impacts in our ex-post assessment. The investment costs of the new technologies, including the opportunity cost of labor, may not pay off due to inadequate integration with the resources of the region. This may be the reason for the negative impact of adoption on the economic stability index and the Coping Strategies Index (components of food security) in Dodoma.

Enfors and Gordon (2008) found that water allocation among members of water user groups in semi-arid Tanzania is skewed towards a few privileged farmers, which could explain the lack of broad positive impacts on stabilizing yields, even in the presence of an improved small-scale water and irrigation system. The overuse of irrigation by some households could have undermined benefits created through the promotion of novel technologies among farmer groups (Ainembabazi et al., 2017). Furthermore, since soil organic matter and moisture levels are factors that can influence the lack of positive results from fertilizer microdosing, weather might be a major determinant of the success of innovations in the rainfed agriculture of semi-arid Dodoma.

These results have clear implications for land management in Eastern Africa. Coupled tied ridges and micro-dosing fertilizers are likely allowing crop diversification and increase food security in more humid areas like Morogoro. This finding could be expanded to other regions in Tanzania with similar biophysical context such as the provinces in the South (Lindi, Ruwuna and Mtwara). Moreover, countries with similar households and farm characteristics such as Kenya, Uganda or Malawi could benefit from such innovations. Previous research in Malawi had shown that, below 500 $mm.yr^{-1}$, tied ridges are not influencing the growth of crops, such as maize (Wiyo et al., 2000). In drier areas, except for the fact that tied ridges coupled to fertilizer micro-dosing contribute to saving water, it does not seem that they should be recommended for increasing productivity.

The innovations studied may interact in complex ways with the available resources. For instance, the effectiveness may be larger for households with good human capital. Research on farming in Sub-Saharan Africa has repeatedly demonstrated the presence of poverty traps. For instance, Tittonell and Giller (2013) show that yield gaps and economic pressures push farmers towards management practices that prioritize short-term gains for survival over long-run soil health and overall sustainability strategies, leading to a poverty trap. Multiple equilibria may exist within a region or country (Kwak & Smith, 2013). Under low baseline levels of productive assets for agricultural production, adopting small-scale innovations may not generate a big enough push to pass thresholds needed for sustained economic viability. More comprehensive interventions addressing resource scarcity at many different levels are then a precondition to enable farmers to use new technologies effectively (Peralta et al., 2018). Hence, studying the differentiated impacts of technology adoption under diverse preconditions remains an important task for future research.

Finally, one way to build upon our research design would be to disentangle the impact of micro-dosing and rainwater harvesting by evaluating them separately. While studying only the combination has the advantage of a higher statistical power, as there are fewer groups and the combined use may be generally more impactful, it also impedes more detailed knowledge. We can also not rule out the possibility that our null result emerges from opposite impacts of the two interventions that cancel each other out.

7. Conclusions

We conducted an interdisciplinary assessment of the impact of two specific technological innovations (water harvesting and fertilizer micro-dosing) on economic, social, and environmental sustainability of farm households in two Tanzanian regions, Dodoma and Morogoro. As discussed in detail in the previous section, such assessment confirms the complex and heterogeneous impacts of new agricultural technologies on small-scale farming in Sub-Saharan Africa.

Our analysis also shows that, in order to draw any conclusion on the impact of new agricultural technologies, it is important to consider a broad set of indicators and to apply a rigorous methodology to obtain unbiased estimates of treatment effects for the many possible impacts at household level. Indeed, although most of our composite sustainability indicators were not affected by the adoption of water harvesting and fertilizer micro-dosing in both regions, some of their components were affected. This sheds light on the need to consider not only summary measures of sustainability, but also to analyze their single components to gain deeper insights into the impacts of technology adoption.

In general, after three years of adoption, such overall impacts were small, although we found important differences between the two regions. By implementing the assessment in regions with different biophysical conditions, important insights can be gained on whether to scale-up interventions. Our results highlight that policies to support technology adoption would likely have to differ between regions and across farm household clusters, since only a sub-sample of farmers may be ready for proper technology adoption, with potential positive impacts on their economic, social and environmental sustainability. However, a more thorough analysis of long-run impacts could help to further inform policy makers, since such technologies may display their full impacts after a proper transition/adaptation period. We also argue that, in some cases, specific barriers may reduce the effectiveness of innovations, such as poverty traps that prioritize short-run survival practices rather than long-run sustainable strategies.

Our conclusions can be reinforced by extending our study, which carries some intrinsic limitations. Evaluation of impacts that go beyond the household would be one important complement to our approach which may miss negative and positive effects transcending the household level. Estimating such impacts would be needed for a more comprehensive welfare and policy analysis. Some of the studied indicators may also interact with each other in complex ways. For instance, the worsening of the Coping Strategies Index in Dodoma for the households that adopted the innovations could be a consequence of the reduced economic sustainability. Such interactions should be properly considered, possibly carrying out a longer-term analysis, based on a further survey round.

Also, further assessments may specialize in testing social impacts of the technologies, while the economic and environmental influences have been prioritized here. For the social pillar, we focused on evaluating changes in food security because this indicator showed a significant difference between 2013 and 2016 and is a main driver of social wellbeing in Tanzania. In addition, availability of data for a longer time horizon (i.e. more than one year before the technology adoption) would have allowed to check the parallel trend assumption for each of the outcomes between the adopters and the non-adopters. Future research on the effectiveness of technology adoption should try to collect data for a longer time period in order to empirically test the key assumptions of the analysis, as well as to catch any effect of technology adoption that may appear only after several years of implementation.

CRediT authorship contribution statement

Diana Escobar Jaramillo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Linda Arata:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Kai Mausch:** Writing – review & editing, Methodology, Investigation. **Paolo Sckokai:** Writing – review & editing, Methodology, Investigation. **Anja Fasse:** Writing – review & editing, Data curation. **Jens Rommel:** Methodology, Investigation, Writing – review & editing. **Pierre Chopin:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared the aggregated household data along with the R code used to perform the analysis.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix 1

XXX

Table A1
Summary statistics of household characteristics of Dodoma sample.

Variable	Units	Dodoma 2013					Dodoma 2016					Difference 2016–2013
		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**
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**
Total labor 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 labor in total labor	%	448	**0.1**	0.1	0	1	420	**0.1**	0.2	0	0.9	**0**
Share of total labor working in land preparation	%	448	**0.2**	0.2	0	0.8	420	**0.2**	0.1	0	0.8	**0**
Share of total labor working in weeding	%	448	**0.3**	0.2	0	1.1	420	**0.3**	0.1	0	0.8	**0**
Share of total labor working in harvesting	%	448	**0.2**	0.2	0	2.2	420	**0.2**	0.1	0	1	**0**
Share of total labor working in planting	%	448	**0.1**	0.1	0	0.6	420	**0.1**	0.1	0	0.4	**0**
Share of total labor 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 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**
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**
Value of productive assets	USD	448	**73.1**	161.6	0	2358.3	420	**75.9**	276.2	0	4879.3	**2.8**

Table A2
Summary statistics of household characteristics of Morogoro sample.

Variable	Units	Morogoro 2013					Morogoro 2016					Difference 2016–2013
		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**
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**
Total labor 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 labor in total labor	%	444	**0.2**	0.3	0	1	390	**0.2**	0.3	0	1	**0**
Share of total labor 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 labor working in weeding	%	444	**0.3**	0.2	0	2.1	390	**0.3**	0.2	0	1.3	**0**
Share of total labor working in harvesting	%	444	**0.2**	0.1	0	0.9	390	**0.2**	0.2	0	1.1	**0**
Share of total labor working in planting	%	444	**0.1**	0.1	0	0.8	390	**0.1**	0.1	0	0.7	**0**
Share of total labor 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 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**

(*continued on next page*)

Table A2 (*continued*)

Variable	Units	Morogoro 2013 n	**mean**	sd	min	max	Morogoro 2016 n	**mean**	Sd	min	max	**Difference 2016–2013**
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**
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**
Value of productive assets	USD	444	**29.9**	63.1	0	603.2	391	**63.7**	331.9	0	6197.1	**33.8**

Table A3
Summary statistics of sustainability indicators for Dodoma.

Pillar	Component	Indicator	Units	Dodoma 2013 (n = 448) Mean	CV (%)	Dodoma 2016 (n = 420) Mean	CV (%)	Difference 2016–2013
Environmental	Soil management	Quantity of applied fertilizer produced outside the farm	Kg / ha	157.7	484	611.8	740	454.1
		Quantity of applied animal manure produced inside the farm	Kg / ha	135.8	580	82.4	592	−53.4
		Crop area perceived as unfertile	% area	0.2	200	0	0	−0.2
		Crop area with perceived decrease in fertility	% area	0.6	67	0.5	80	−0.1
		Crop area under legume	% area	0.3	67	0.2	100	−0.1
		Crop residues left on the field	% area	0.3	133	0.2	150	−0.1
		Intent to invest in soil fertility	% area	0.8	50	0.5	80	−0.3
		Tree density	Number of trees / ha	11.4	532	9.4	400	−2
		Area under erosion control measures	% area	0.3	133	0.2	200	−0.1
	Water management	Presence of irrigation	Yes – No	0	0	0	0	0
		Rainfall water use efficiency	Kg / ha / mm of rainfall	0.5	200	0.6	117	0.1
		Change in water consumption	Liters/day	7.1	549	−20.9	−642	−28
		Other form of water harvesting	Yes – No	0.4	125	0.2	200	−0.2
		Water use conflict	% of amount	0.1	300	0	0	−0.1
	Agricultural diversity	Tree diversity	Number of species	2.9	83	2.8	64	−0.1
		Crop diversity	Number of species	3.7	43	3.3	39	−0.4
		Livestock diversity	Number of species	1.3	100	1.8	72	0.5
Economic	Crop profitability	Crop gross margin	USD / ha	159	229	206.4	129	47.4
		Crop expenditures	USD / ha	35.8	206	53.4	171	17.6
		Labor productivity	USD / person	0.6	217	0.5	100	−0.1
		Post-harvest loss	% amount	3.1	319	2.1	205	−1
	Profitability	Net household income	USD	982.5	133	1368.8	126	386.3
	Stability	High income fluctuation	Yes – No	0.5	100	0.5	100	0
		Has savings	Yes – No	0.2	200	0.8	50	0.6
	Vulnerability to shocks	Loss of income due to shock	USD	349.6	202	424.4	161	74.8
		High severity of shock	Yes – No	0.7	57	0.7	71	0
		Time to recover after shock	Number of months	25.6	130	18.5	588	−7.1
Social	Food security	Potential Food Availability index (PFAI)	Ratio	2	75	2	140	0
		Months of inadequate food provisioning	Number of months	5.8	62	4.8	77	−1
		Food Consumption Score (FCS)	Score	45.8	35	46.9	38	1.1
		Coping Strategies Index (CSI)	Score	33.8	88	6.3	244	−27.5
	Health	Health insurance binary	Yes – No	0.3	133	0.3	167	0
		Healthy household members	% of people	0.8	37	0.8	25	0
	Wellbeing	Hours worked	Hours/active household member	664.3	120	707.2	97	42.9
		Perceived deterioration of household situation	Yes – No	0.5	100	0.4	125	−0.1
		High impact of income fluctuations on wellbeing	Yes – No	0.5	100	0.4	125	−0.1
	Social capital	Information network	Number of sources	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	% of area	0	0	0	0	0
		Secure land	% of area	0.5	100	0.5	100	0
		Land use conflict	% of area	0.1	200	0	0	−0.1

Table A4
Summary statistics of sustainability indicators for Morogoro.

Pillar	Component	Indicator	Units	Morogoro 2013 (n = 444)		Morogoro 2016 (n = 391)		Difference 2016–2013
				Mean	CV (%)	Mean	CV (%)	
Environmental	Soil management	Quantity of applied fertilizer produced outside the farm	Kg / ha	2	930	298.4	1424	296.4
		Quantity of applied animal manure produced inside the farm	Kg / ha	26	1316	0.5	1240	−25.5
		Crop area perceived as unfertile	% area	0.1	200	0	0	−0.1
		Crop area with perceived decrease in fertility	% area	0.5	100	0.3	133	−0.2
		Crop area under legume	% area	0.1	100	0.2	100	0.1
		Crop residues left on the field	% area	0.4	125	0.1	200	−0.3
		Intent to invest in soil fertility	% area	0.3	167	0.3	133	0
		Tree density	Number of trees / ha	4.6	165	7.9	194	3.3
		Area under erosion control measures	% area	0.2	150	0.2	150	0
	Water management	Presence of irrigation	Yes – No	0	0	0.1	300	0.1
		Rainfall water use efficiency	Kg / ha / mm of rainfall	0.7	243	0.5	160	−0.2
		Change in water consumption	Liters/day	1.1	3573	−2.5	−3328	−3.6
		Water use conflict	% of amount	0.1	200	0	0	−0.1
	Agricultural diversity	Tree diversity	Number of species	1.8	100	2.4	67	0.6
		Crop diversity	Number of species	2.1	48	2.8	39	0.7
		Livestock diversity	Number of species	0.8	87	0.9	67	0.1
Economic	Crop profitability	Crop gross margin	USD / ha	609.3	175	391	210	−218.3
		Crop expenditures	USD / ha	195.8	589	191.8	173	−4
		Labor productivity	USD / person	1.6	125	1.1	173	−0.5
		Post-harvest loss	% amount	1.8	322	3.5	249	1.7
	Profitability	Net household income	USD	1483.9	187	1396.2	117	−87.7
	Stability	High income fluctuation	Yes – No	0.3	133	0.6	83	0.3
		Has savings	Yes – No	0.4	125	0.7	71	0.3
	Vulnerability to shocks	Loss of income due to shock	USD	155.8	274	768.2	136	612.4
		High severity of shock	Yes – No	0.4	125	0.8	50	0.4
		Time to recover after shock	Number of months	11.9	223	48	691	36.1
Social	Food security	Potential Food Availability index (PFAI)	Ratio	2.7	78	2.7	74	0
		Months of inadequate food provisioning	Number of months	5.1	96	4	88	−1.1
		Food Consumption Score (FCS)	Score	53.2	31	53.8	29	0.6
		Coping Strategies Index (CSI)	Score	16.2	149	7.3	225	−8.9
	Health	Health insurance binary	Yes – No	0.1	300	0.2	200	0.1
		Healthy household members	% of people	0.9	33	0.8	37	−0.1
	Wellbeing	Hours worked	Hours/active household member	532.1	154	627	124	94.9
		Perceived deterioration of household situation	Yes – No	0.3	167	0.6	83	0.3
		High impact of income fluctuations on wellbeing	Yes – No	0.2	200	0.5	100	0.3
	Social capital	Information network	Number of sources	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	% of area	0.1	300	0	0	−0.1
		Secure land	% of area	0.1	300	0.3	133	0.2
		Land use conflict	% of area	0.1	300	0.1	300	0

Table A5
Balance test on the covariates before matching in Dodoma.

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
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 labor 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
Share of cropped area dedicated to maize	0.0900	0.0793	0.0807	1.0838	0.46
Hired labor	0.0457	0.0530	−0.0556	0.7873	0.63
Land security index	0.4995	0.4783	0.1075	1.0775	0.33

Table A6
Balance test on the covariates after matching in Dodoma.

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
Age of household head	49.1961	49.2164	−0.0013	0.8165	0.93
Education of household head	4.2579	4.2338	0.0077	0.8427	0.87
Total labor invested per land unit	568.5142	528.7356	0.0558	1.2358	0.91
Total area managed by the household	2.4458	2.2996	0.0694	0.8729	0.43
Share of total area used for cropping	0.8850	0.8832	0.0092	0.9553	0.57
Share of cropped area dedicated to cash crops	0.0986	0.0931	0.0423	0.7936	0.38
Value of productive assets	76.9855	68.1113	0.0360	0.8443	0.19
Share of cropped area dedicated to maize	0.0886	0.0994	−0.0814	0.8123	0.84
Hired labor	0.0474	0.0407	0.0507	1.1500	0.76
Land security index	0.4983	0.4999	−0.0084	0.9987	0.39

Table A7
Balance test on the covariates before matching in Morogoro.

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
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 labor	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
Value of productive assets	44.8184	28.9372	0.1621	2.8466	0.20
Share of cropped area dedicated to maize	0.5932	0.6271	−0.1077	1.2415	0.41
Total labor 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

Table A8
Balance test on the covariates after matching in Morogoro.

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	p-value
Age of household head	47.1250	48.6643	−0.0918	0.7611	0.63
Education of household head	5.3895	5.3600	0.0099	0.8957	0.39
Hired labor	0.1314	0.1223	0.0367	1.3679	0.73
Total area managed by the household	2.3387	2.4327	−0.0546	0.2872	0.20
Share of total area used for cropping	0.8760	0.8790	−0.0142	1.5276	0.73
Share of cropped area dedicated to cash crops	0.2274	0.2115	0.0589	1.2417	0.99
Value of productive assets	37.4723	30.9505	0.0666	2.5788	0.27
Share of cropped area dedicated to maize	0.5846	0.6016	−0.0540	1.2901	0.54
Total labor invested per land unit	644.1509	671.7603	−0.0444	0.6400	0.66
Land security index	0.3940	0.3816	0.0566	0.0452	0.49

Table A9
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	0.097**	(0.05)	−0.004	(0.04)
Hired labor	−1.332**	(0.63)	−0.951	(0.89)
Total area managed by the household	0.081	(0.06)	0.045	(0.05)
Share of total area used for cropping	0.474	(0.72)	0.837	(0.53)
Share of cropped area dedicated to cash crops	−0.913	(0.71)	−1.318*	(0.77)
Share of cropped area dedicated to maize	−0.735	(0.63)	0.491	(0.85)
Total labor invested per land unit	−0.00002	(0.00)	−0.00001	(0.00)
Land security index	1.481*	(0.76)	0.649	(0.61)
Value of productive assets	0.003	(0.00)	0.001*	(0.00)
Constant	−2.988***	(1.03)	−1.909***	(0.70)
Observations	388		420	
Log Likelihood	−172.37		−235.52	
Akaike Inf. Crit.	366.75		493.05	

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

Table A10
Sample sizes before and after matching algorithm was applied for the two study regions.

Number of households	Dodoma	Morogoro
Treated group*		
Before matching	110	69
After matching	106	64
Control group		
Before matching	310	319
After matching	278	260
Matching algorithm	10:1 nearest neighbor matching with replacement and caliper of 0.1	

* Adopters of both technologies: rainwater harvesting and fertilizer micro-dosing.

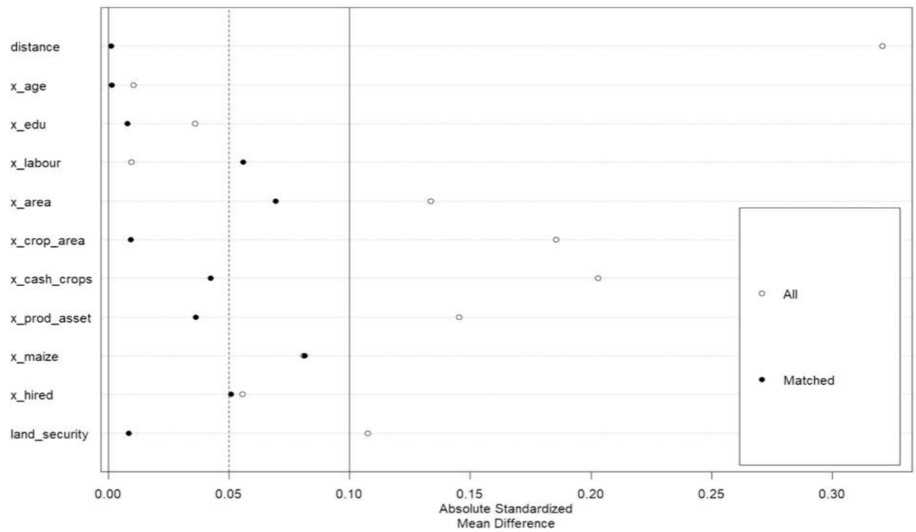

Fig. A1. Absolute standardized mean differences of matched sample from Dodoma.

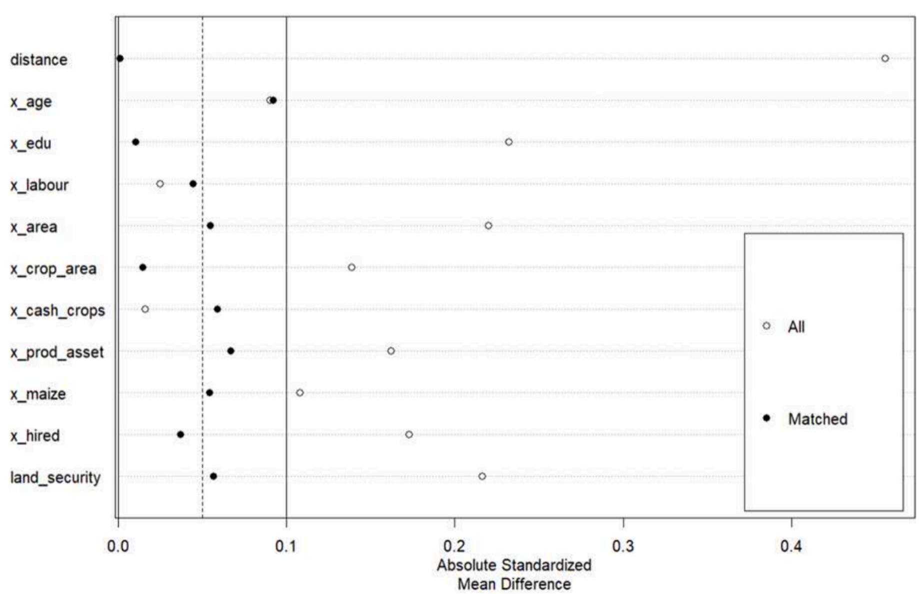

Fig. A2. Absolute standardized mean differences of matched sample from Morogoro.

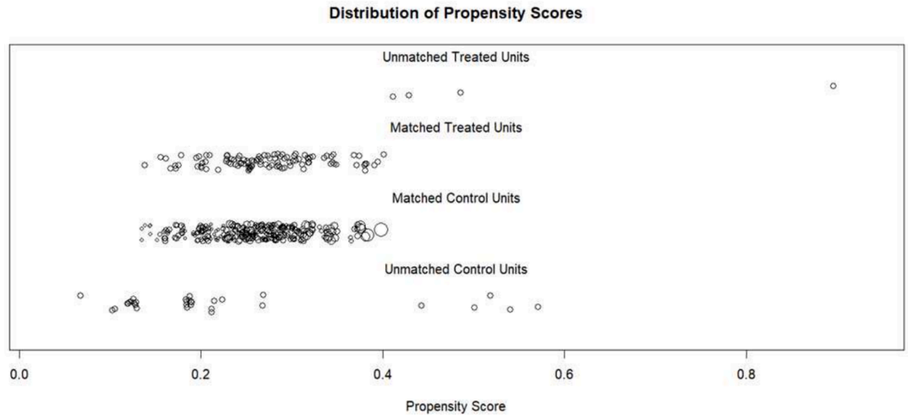

Fig. A3. Distribution of the propensity scores of the sampled households in Dodoma.

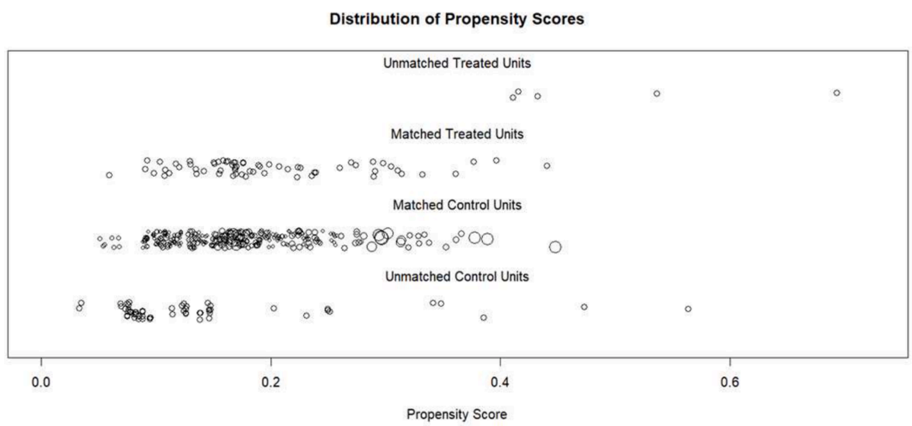

Fig. A4. Distribution of the propensity scores of the sampled households in Morogoro.

Table A11
Average Treatment Effect on the Treated (ATT) of Rainwater Harvesting and Fertilizer Micro-dosing Adoption in Dodoma and Morogoro, 2013–2016 (Before matching algorithm applied).

			Dodoma				Morogoro			
Sustainability pillar	Outcome variable:	Units	**ATT**	SD	Difference between mean values 2016–2013 of Matched Control Group	SD	**ATT**	SD	Difference between mean values 2016–2013 of Matched Control Group	SD
Environmental	Quantity of applied fertilizer produced outside the farm	Kg / ha	**−614.81***	(332.26)	617.22**	(299.07)	**−362.84**	(263.54)	362.99	(263.53)
	Quantity of applied animal manure produced inside the farm	Kg / ha	**19.72**	(123.32)	−64.00	(46.05)	**−19.45**	(46.48)	−24.39	(20.72)
	Presence of irrigation	Yes – No	**−0.02**	(0.02)	0.02	(0.01)	**0.01**	(0.04)	0.03**	(0.01)
	Rainfall water use efficiency	Kg / ha / mm of rainfall	**0.11**	(0.07)	0.59***	(0.04)	**−0.10**	(0.07)	0.53***	(0.05)
	Change in household Water consumption	Liters / day	**−33.83***	(19.24)	−18.96**	(7.61)	**−23.97****	(11.84)	1.72	(5.31)
	Water use conflict	% of amount	**0.07****	(0.03)	−0.13***	(0.02)	**0.03**	(0.04)	−0.01	(0.02)
	Soil management index	0 to 1	**−0.01**	(0.02)	−0.03***	(0.01)	**0.01**	(0.02)	0.02**	(0.01)

(*continued on next page*)

Table A11 (*continued*)

Sustainability pillar	Outcome variable:	Units	Dodoma ATT	SD	Difference between mean values 2016–2013 of Matched Control Group	SD	Morogoro ATT	SD	Difference between mean values 2016–2013 of Matched Control Group	SD
	Water management index	0 to 1	**−0.01**	(0.02)	0.07***	(0.01)	**−0.01**	(0.02)	−0.00	(0.01)
	Agricultural diversity index	0 to 1	**−0.03***	(0.02)	0.01	(0.01)	**0.03**	(0.02)	0.07***	(0.01)
	Environmental Sustainability index	0 to 1	**−0.02**	(0.01)	0.01**	(0.01)	**0.01**	(0.01)	0.03***	(0.00)
Economic	Crop gross margin per ha	USD / ha	**0.75**	(41.54)	56.83**	(22.33)	**−15.34**	(129.89)	−217.20**	(84.52)
	Crop expenditures per ha	USD / ha	**17.27**	(14.62)	14.84**	(5.95)	**89.99**	(84.19)	−35.63	(76.99)
	Labor productivity	USD / person	**0.06**	(0.11)	−0.04	(0.06)	**0.29**	(0.24)	−0.56***	(0.17)
	Post-harvest loss	% amount	**−1.27**	(1.25)	−0.71	(0.62)	**0.83**	(1.39)	1.68***	(0.54)
	Net household income	USD	**40.56**	(181.94)	1,357.25***	(100.62)	**−105.8**	(171.05)	1,419.75***	(96.75)
	High income fluctuation	Yes – No	**0.08**	(0.08)	−0.07*	(0.04)	**−0.03**	(0.08)	0.39***	(0.04)
	Has savings	Yes – No	**0.11***	(0.06)	0.59***	(0.03)	**0.02**	(0.08)	0.32***	(0.03)
	Loss of income due to shock	USD	**145.93**	(138.57)	37.42	(44.43)	**301.30**	(185.99)	558.61***	(53.21)
	High severity of shock	Yes – No	**0.04**	(0.07)	−0.04	(0.04)	**0.01**	(0.08)	0.46***	(0.03)
	Months to recover after shock	Number of months	**14.19**	(19.19)	−10.52***	(3.38)	**2.82**	(48.59)	36.07**	(18.27)
	Crop profitability index	0 to 1	**−0.00**	(0.01)	0.00	(0.01)	**0.02**	(0.02)	−0.09***	(0.01)
	Profitability index	0 to 1	**−0.06**	(0.04)	0.07***	(0.02)	**0.04**	(0.06)	0.02	(0.02)
	Stability index	0 to 1	**−0.1***	(0.05)	0.33***	(0.03)	**−0.10***	(0.06)	0.03	(0.03)
	Vulnerability to shocks reduction index	0 to 1	**−0.04**	(0.02)	0.06***	(0.01)	**0.00**	(0.03)	−0.12***	(0.01)
	Economic sustainability index	0 to 1	**−0.05****	(0.02)	0.12***	(0.01)	**−0.01**	(0.03)	−0.04***	(0.01)
Social	Potential Food Availability index (PFAI)	Kcal produced & purchased / Kcal needs / household / year	**0.12**	(0.27)	−0.00	(0.2)	**−0.18**	(0.34)	0.08	(0.12)
	Months of inadequate food provisioning	Number of months	**−0.06**	(0.51)	−1.00***	(0.29)	**−1.74****	(0.75)	−0.72**	(0.32)
	Food Consumption Score (FCS)	From 0 to 112	**−0.22**	(2.44)	1.18	(1.14)	**5.03***	(2.7)	−0.23	(1.09)
	Coping Strategies Index (CSI)	Score for frequency and severity of hunger facing measures	**4.17**	(3.01)	−28.68***	(1.93)	**−9.68****	(4.23)	−7.25***	(1.54)
	Food security index	0 to 1	**−0.02**	(0.02)	0.11***	(0.01)	**0.09*****	(0.03)	0.04***	(0.01)
	Social sustainability index	0 to 1	**0.00**	(0.02)	0.00	(0.01)	**0.01**	(0.01)	−0.02***	(0.01)
	Overall sustainability index	0 to 1	**−0.02***	(0.01)	0.04***	(0.01)	**0.00**	(0.01)	−0.01*	(0.01)

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

Table A12
P-values of the one-sided test of the sensitivity analysis in Dodoma (null-hypothesis: no effect of the treatment).

Γ	Quantity of applied fertilizer produced outside the farm	Change in household Water consumption	Stability index	Economic sustainability index	Coping Strategies Index CSI
1	0.07	0.01	0.02	0.00	0.03
1.1	0.08	0.02	0.06	0.01	0.07
1.2	0.09	0.04	0.11	0.03	0.12
1.3	0.10	0.07	0.19	0.06	0.19
1.4	0.11	0.11	0.28	0.11	0.26
1.5	0.12	0.16	0.39	0.17	0.35
1.6	0.13	0.21	0.50	0.25	0.44
1.7	0.14	0.26	0.60	0.34	0.53
1.8	0.15	0.32	0.69	0.43	0.61
1.9	0.16	0.38	0.76	0.51	0.68
2	0.17	0.43	0.82	0.60	0.74

Table A13
P-values of the one-sided test of the sensitivity analysis in Morogoro (null-hypothesis: no effect of the treatment).

Γ	Agricultural diversity index	Months of inadequate food provisioning	Food security index
1	0.01	0.03	0.00
1.1	0.03	0.06	0.01
1.2	0.06	0.11	0.02
1.3	0.09	0.16	0.03
1.4	0.14	0.23	0.05
1.5	0.19	0.30	0.08
1.6	0.25	0.38	0.11
1.7	0.32	0.46	0.15
1.8	0.38	0.53	0.20
1.9	0.45	0.60	0.25
2	0.52	0.66	0.30

Table A14
P-values of the one-sided test of the sensitivity analysis in Morogoro (null-hypothesis: no effect of the treatment).

Γ	Coping Strategies Index CSI
1	2.06E-04
2	4.59E-02
3	2.73E-01
4	5.63E-01
5	7.74E-01
6	8.93E-01
7	9.52E-01
8	9.79E-01
9	9.91E-01
10	9.96E-01

References

Abu-Bakar, H., Williams, L., & Hallett, S. H. (2021). A review of household water demand management and consumption measurement. *Journal of Cleaner Production, 292*, Article 125872. https://doi.org/10.1016/j.jclepro.2021.125872

Acosta-Alba, I., Chia, E., & Andrieu, N. (2019). The LCA4CSA framework: Using life cycle assessment to strengthen environmental sustainability analysis of climate smart agriculture options at farm and crop system levels. *Agricultural Systems, 171*, 155–170. https://doi.org/10.1016/j.agsy.2019.02.001

Adolwa, I. S., Schwarze, S., & Buerkert, A. (2019). Impacts of integrated soil fertility management on yield and household income: The case of Tamale (Ghana) and Kakamega (Kenya). *Ecological Economics, 161*, 186–192. https://doi.org/10.1016/j.ecolecon.2019.03.023

Ainembabazi, J. H., van Asten, P., Vanlauwe, B., Ouma, E., Blomme, G., Birachi, E. A., Nguezet, P. M. D., Mignouna, D. B., & Manyong, V. M. (2017). Improving the speed of adoption of agricultural technologies and farm performance through farmer groups: Evidence from the Great Lakes region of Africa. *Agricultural Economics, 48* (2), 241–259. https://doi.org/10.1111/agec.12329

Angelsen, A., & Dokken, T. (2018). Climate exposure, vulnerability and environmental reliance: A cross-section analysis of structural and stochastic poverty. *Environment and Development Economics*, *23*(3), 257–278. Cambridge Core. https://doi.org/10.1017/S1355770X18000013.

Anriquez, G., Foster, W., Ortega, J., & Santos Rocha, J. (2021). In search of economically significant food losses: Evidence from Tunisia and Egypt. *Food Loss and Waste: Evidence for Effective Policies, 98*, Article 101912. https://doi.org/10.1016/j.foodpol.2020.101912

Antunes, P., Santos, R., Cosme, I., Osann, A., Calera, A., De Ketelaere, D., Spiteri, A., Mejuto, M. F., Andreu, J., Momblanch, A., Nino, P., Vanino, S., Florian, V., Chitea, M., Çetinkaya, C. P., Sakamoto, M. S., Kampel, M., Palacio Sanchez, L. A., Abdin, A. E., & Nagarajan, S. (2017). A holistic framework to assess the sustainability of irrigated agricultural systems. *Cogent Food & Agriculture, 3*(1), 1323542. https://doi.org/10.1080/23311932.2017.1323542

Arata, L., & Sckokai, P. (2016). The Impact of Agri-environmental Schemes on Farm Performance in Five E.U. Member States: A DID-Matching Approach. *Land Economics, 92*(1), 167–186.

Asminaya, N., Purwanto, B., Nahrowi, N., Ridwan, W., & Atabany, A. (2018). Ecological Sustainability of smallholder dairy farm with leisa pattern. *Journal of the Indonesian Tropical Animal Agriculture, 43*(60), 412–420.

Aune, J. B., & Bationo, A. (2008). Agricultural intensification in the Sahel – The ladder approach. *Agricultural Systems, 98*(2), 119–125. https://doi.org/10.1016/j.agsy.2008.05.002

Austin, P. C. (2009). Type I error rates, coverage of confidence intervals, and variance estimation in propensity-score matched analyses. *The International Journal of Biostatistics, 5*, 13. https://doi.org/10.2202/1557-4679.1146

Baccar, M., Bouaziz, A., Dugué, P., Gafsi, M., & Le Gal, P.-Y. (2019). The determining factors of farm sustainability in a context of growing agricultural intensification. *Agroecology and Sustainable Food Systems, 43*(4), 386–408. https://doi.org/10.1080/21683565.2018.1489934

Bachke, M. E. (2019). Do farmers' organizations enhance the welfare of smallholders? Findings from the Mozambican national agricultural survey. *Food Policy, 89*, Article 101792. https://doi.org/10.1016/j.foodpol.2019.101792

Barrett, C. B., Bachke, M. E., Bellemare, M. F., Michelson, H. C., Narayanan, S., & Walker, T. F. (2012). Smallholder participation in contract farming: Comparative evidence from five countries. *World Development, 40*(4), 715–730. https://doi.org/10.1016/j.worlddev.2011.09.006

Becerril, J., & Abdulai, A. (2010). The impact of improved maize varieties on poverty in Mexico: A propensity score-matching approach. *World Development, 38*, 1024–1035. https://doi.org/10.1016/j.worlddev.2009.11.017

Bernués, A., Ruiz, R., Olaizola, A., Villalba, D., & Casasús, I. (2011). Sustainability of pasture-based livestock farming systems in the European Mediterranean context: Synergies and trade-offs. *Special Issue: Assessment for Sustainable Development of Animal Production Systems, 139*(1), 44–57. https://doi.org/10.1016/j.livsci.2011.03.018

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., & Stroosnijder, L. (2012). Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review. *Recent Advances in Water Resources Management, 47–48*, 139–151. https://doi.org/10.1016/j.pce.2011.08.015

Bielders, C., & Gérard, B. (2014). Millet response to microdose fertilization in south–western Niger: Effect of antecedent fertility management and environmental factors. *Field Crops Research, 171*. https://doi.org/10.1016/j.fcr.2014.10.008

Binder, C. R., Feola, G., & Steinberger, J. K. (2010). Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environmental Impact Assessment Review, 30*(2), 71–81. https://doi.org/10.1016/j.eiar.2009.06.002

Brüssow, K., Faße, A., & Grote, U. (2017). Implications of climate-smart strategy adoption by farm households for food security in Tanzania. *Food Security, 9*(6), 1203–1218. https://doi.org/10.1007/s12571-017-0694-y

Caliendo, M., & Kopeinig, S. (2008). Some practical guidance for the implementation of propensity score matching. *Journal of Economic Surveys, 22*(1), 31–72. https://doi.org/10.1111/j.1467-6419.2007.00527.x

Carney, D. (1998). *Sustainable rural livelihoods: What contribution can we make?* Department for International Development London.

Chabé-Ferret, S. (2015). Analysis of the bias of Matching and Difference-in-Difference under alternative earnings and selection processes. *Journal of Econometrics, 185*(1), 110–123. https://doi.org/10.1016/j.jeconom.2014.09.013

Chabé-Ferret, S., & Subervie, J. (2013). How much green for the buck? Estimating additional and windfall effects of French agro-environmental schemes by DID-matching. *Journal of Environmental Economics and Management, 65*, 12–27. https://doi.org/10.1016/j.jeem.2012.09.003

Chilagane, E. A., Saidia, P. S., Kahimba, F. C., Asch, F., Germer, J., Graef, F., Swai, E., & Rweyemamu, C. L. (2020). Effects of fertilizer micro-dose and in situ rain water harvesting technologies on growth and yield of pearl millet in a semi-arid environment. *Agricultural Research*, 1–13.

Chimweta, M., Nyakudya, I. W., & Jimu, L. (2018). Fertility status of cultivated floodplain soils in the Zambezi Valley, northern Zimbabwe. *The 17th WaterNet/WARFSA/GWPSA Symposium: Integrated Water Resources Management: Water Security, Sustainability and Development in Eastern and Africa Southern, 105*, 147–153. https://doi.org/10.1016/j.pce.2017.12.005

Chopin, P., Guindé, L., Causeret, F., Bergkvist, G., & Blazy, J.-M. (2019). Integrating stakeholder preferences into assessment of scenarios for electricity production from locally produced biomass on a small island. *Renewable Energy, 131*, 128–136. https://doi.org/10.1016/j.renene.2018.06.031

Chopin, P., Mubaya, C. P., Descheemaeker, K., Öborn, I., & Bergkvist, G. (2021). Avenues for improving farming sustainability assessment with upgraded tools, sustainability framing and indicators. A review. *Agronomy for Sustainable Development, 41*(2), 19. https://doi.org/10.1007/s13593-021-00674-3

Clover, J., & Eriksen, S. (2009). The effects of land tenure change on sustainability: Human security and environmental change in southern African savannas. *Thematic Set: The Sustainability of Southern African Savannas: Threats and Opportunities, 12*(1), 53–70. https://doi.org/10.1016/j.envsci.2008.10.012

De Cock, N., D'Haese, M., Vink, N., van Rooyen, C. J., Staelens, L., Schönfeldt, H. C., & D'Haese, L. (2013). Food security in rural areas of Limpopo province, South Africa. *Food Security, 5*(2), 269–282. https://doi.org/10.1007/s12571-013-0247-y

Dile, Y. T., Karlberg, L., Temesgen, M., & Rockstrom, J. (2013). The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. *Agriculture, Ecosystems & Environment, 181*, 69–79. https://doi.org/10.1016/j.agee.2013.09.014

Dillon, A. (2011). The effect of irrigation on poverty reduction, asset accumulation, and informal insurance: Evidence from Northern Mali. *World Development, 39*(12), 2165–2175. https://doi.org/10.1016/j.worlddev.2011.04.006

Duflo, E., Glennerster, R., & Kremer, M. (2007). Chapter 61 Using Randomization in Development Economics Research: A Toolkit. In T. P. Schultz, & J. A. Strauss (Eds.), *Handbook of Development Economics* (Vol. 4, pp. 3895–3962). Elsevier. https://doi.org/10.1016/S1573-4471(07)04061-2.

Ellis-Jones, J., & Tengberg, A. (2000). The impact of indigenous soil and water conservation practices on soil productivity: Examples from Kenya, Tanzania and Uganda. *Land Degradation & Development, 11*(1), 19–36. https://doi.org/10.1002/(SICI)1099-145X(200001/02)11:1<19::AID-LDR357>3.0.CO;2-2

Enfors, E. I., & Gordon, L. J. (2008). Dealing with drought: The challenge of using water system technologies to break dryland poverty traps. *Local Evidence on Vulnerabilities and Adaptations to Global Environmental Change, 18*(4), 607–616. https://doi.org/10.1016/j.gloenvcha.2008.07.006

Escribano, M., Díaz-Caro, C., & Mesias, F. J. (2018). A participative approach to develop sustainability indicators for dehesa agroforestry farms. *Science of The Total Environment, 640–641*, 89–97. https://doi.org/10.1016/j.scitotenv.2018.05.297

Fadul-Pacheco, L., Wattiaux, M. A., Espinoza-Ortega, A., Sánchez-Vera, E., & Arriaga-Jordán, C. M. (2013). Evaluation of sustainability of smallholder dairy production systems in the highlands of Mexico during the rainy season. *Agroecology and Sustainable Food Systems, 37*(8), 882–901. https://doi.org/10.1080/21683565.2013.775990

Faltermeier, L., & Abdulai, A. (2009). The impact of water conservation and intensification technologies: Empirical evidence for rice farmers in Ghana. *Agricultural Economics, 40*(3), 365–379. https://doi.org/10.1111/j.1574-0862.2009.00383.x

Felice, V. D., Mancinelli, R., Proulx, R., & Campiglia, E. (2012). A multivariate analysis for evaluating the environmental and economical aspects of agroecosystem sustainability in central Italy. *Journal of Environmental Management, 98*, 119–126. https://doi.org/10.1016/j.jenvman.2011.12.015

Firbank, L. G., Elliott, J., Field, R. H., Lynch, J. M., Peach, W. J., Ramsden, S., & Turner, C. (2018). Assessing the performance of commercial farms in England and Wales: Lessons for supporting the sustainable intensification of agriculture. *Food and Energy Security, 7*(4), e00150.

Frelat, R., Lopez-Ridaura, S., Giller, K., Herrero, M., Douxchamps, S., Djurfeldt, A., Erenstein, O., Henderson, B., Berresaw, M., Paul, B., Rigolot, C., Ritzema, R., Rodriguez, D., Van Asten, P. J. A., & Van Wijk, M. (2015). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences, 113*, 201518384. https://doi.org/10.1073/pnas.1518384112

Gaviglio, A., Bertocchi, M., & Demartini, E. (2017). A tool for the sustainability assessment of farms: Selection, adaptation and use of indicators for an Italian case study. *Resources, 6*(4). https://doi.org/10.3390/resources6040060

Germer, J., Herrman, L., Mahoo, H., Swai, E., Graef, F., Kahimba, F., Asch, F., Tumbo, S., Makoro, B., Kimaro, A., Schäfer, M., Saidia, P., & Chilagane, E. (2021). Trans-SEC Factsheet 1a. *Trans-SEC.* http://project2.zalf.de/trans-sec/public/media/factsheets/Trans-SECfactsheet1a.pdf.

Gómez-Limón, J. A., & Sanchez-Fernandez, G. (2010). Empirical evaluation of agricultural sustainability using composite indicators. *Ecological Economics, 69*(5), 1062–1075. https://doi.org/10.1016/j.ecolecon.2009.11.027

Graef, F., Sieber, S., Mutabazi, K., Asch, F., Biesalski, H., Bitegeko, J., Bokelmann, W., Brüntrup, M., Dietrich, O., Elly, N., Faße, A., Germer, J., Grote, U., Herrmann, L., Herrmann, R., Hoffmann, H., Kahimba, F., Kaufmann, B., Kersebaum, K., & Uckert, G. (2014). Framework for participatory food security research in rural food value chains. *Global Food Security, 3*, 8–15. https://doi.org/10.1016/j.gfs.2014.01.001

Graef, F., Uckert, G., Schindler, J., König, H. J., Mbwana, H. A., Fasse, A., Mwinuka, L., Mahoo, H., Kaburire, L. N., Saidia, P., Yustas, Y. M., Silayo, V., Makoko, B., Kissoly, L., Lambert, C., Kimaro, A., Sieber, S., Hoffmann, H., Kahimba, F. C., & Mutabazi, K. D. (2017). Expert-based ex-ante assessments of potential social, ecological, and economic impacts of upgrading strategies for improving food security in rural Tanzania using the ScalA-FS approach. *Food Security, 9*(6), 1255–1270. https://doi.org/10.1007/s12571-016-0639-x

Habtemariam, L. T., Mgeni, C. P., Mutabazi, K. D., & Sieber, S. (2019). The farm income and food security implications of adopting fertilizer micro-dosing and tied-ridge technologies under semi-arid environments in central Tanzania. *Journal of Arid Environments, 166*, 60–67. https://doi.org/10.1016/j.jaridenv.2019.02.011

Haile, B., Azzarri, C., Roberts, C., & Spielman, D. J. (2017). Targeting, bias, and expected impact of complex innovations on developing-country agriculture: Evidence from Malawi. *Agricultural Economics, 48*(3), 317–326. https://doi.org/10.1111/agec.12336

Haileslassie, A., Craufurd, P., Thiagarajah, R., Kumar, S., Whitbread, A., Rathor, A., Blummel, M., Ericsson, P., & Kakumanu, K. R. (2016). Empirical evaluation of sustainability of divergent farms in the dryland farming systems of India. *Ecological Indicators, 60*, 710–723. https://doi.org/10.1016/j.ecolind.2015.08.014

Hansen, J. W. (1996). Is agricultural sustainability a useful concept? *Agricultural Systems, 50*(2), 117–143. https://doi.org/10.1016/0308-521X(95)00011-S

Heckman, J. J., Ichimura, H., & Todd, P. E. (1997). Matching as an econometric evaluation estimator: Evidence from evaluating a job training programme. *The Review of Economic Studies, 64*(4), 605–654. https://doi.org/10.2307/2971733

Herrmann, R., Nkonya, E., & Faße, A. (2018). Food value chain linkages and household food security in Tanzania. *Food Security, 10*(4), 827–839. https://doi.org/10.1007/s12571-018-0792-5

Hoang, L. A., Castella, J.-C., & Novosad, P. (2006). Social networks and information access: Implications for agricultural extension in a rice farming community in northern Vietnam. *Agriculture and Human Values, 23*(4), 513–527. https://doi.org/10.1007/s10460-006-9013-5

Janker, J., Mann, S., & Rist, S. (2019). Social sustainability in agriculture – A system-based framework. *Journal of Rural Studies, 65*, 32–42. https://doi.org/10.1016/j.jrurstud.2018.12.010

Jansen, H. G. P., Pender, J., Damon, A., Wielemaker, W., & Schipper, R. (2006). Policies for sustainable development in the hillside areas of Honduras: A quantitative livelihoods approach. *Agricultural Economics, 34*(2), 141–153. https://doi.org/10.1111/j.1574-0864.2006.00114.x

Jones, A. D., Ngure, F. M., Pelto, G., & Young, S. L. (2013). What are we assessing when we measure food security? A compendium and review of current metrics. *Advances in Nutrition, 4*(5), 481–505. https://doi.org/10.3945/an.113.004119

Kansiime, M. K., van Asten, P., & Sneyers, K. (2018). Farm diversity and resource use efficiency: Targeting agricultural policy interventions in East Africa farming systems. *NJAS: Wageningen. Journal of Life Sciences, 85*(1), 32–41. https://doi.org/10.1016/j.njas.2017.12.001

Kassie, M., Köhlin, G., Bluffstone, R., & Holden, S. (2011). Are soil conservation technologies "win-win?" A case study of Anjeni in the north-western Ethiopian highlands. *Natural Resources Forum, 35*(2), 89–99. https://doi.org/10.1111/j.1477-8947.2011.01379.x

Kassie, M., Pender, J., Yesuf, M., Kohlin, G., Bluffstone, R., & Mulugeta, E. (2008). Estimating returns to soil conservation adoption in the northern Ethiopian highlands. *Agricultural Economics, 38*(2), 213–232. https://doi.org/10.1111/j.1574-0862.2008.00295.x

Kebebe, E. G. (2017). Household nutrition and income impacts of using dairy technologies in mixed crop–livestock production systems. *Australian Journal of Agricultural and Resource Economics, 61*(4), 626–644. https://doi.org/10.1111/1467-8489.12223

Kebede, Y., Gunjal, K., & Coffin, G. (1990). Adoption of New Technologies in Ethiopian Agriculture: The Case of Tegulet-Bulga District, Shoa Province. *Agricultural Economics, 4*(1), 27–43. https://doi.org/10.1111/j.1574-0862.1990.tb00103.x

Khonje, M., Manda, J., Alene, A. D., & Kassie, M. (2015). Analysis of adoption and impacts of improved maize varieties in Eastern Zambia. *World Development, 66*, 695–706. https://doi.org/10.1016/j.worlddev.2014.09.008

Kissoly, L., Faße, A., & Grote, U. (2017). The integration of smallholders in agricultural value chain activities and food security: Evidence from rural Tanzania. *Food Security, 9*(6), 1219–1235. https://doi.org/10.1007/s12571-016-0642-2

Kuyah, S., Sileshi, G. W., Nkurunziza, L., Chirinda, N., Ndayisaba, P. C., Dimobe, K., & Öborn, I. (2021). Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. *Agronomy for Sustainable Development, 41*(2), 16. https://doi.org/10.1007/s13593-021-00673-4

Kwak, S., & Smith, S. C. (2013). Regional agricultural endowments and shifts of poverty trap equilibria: Evidence from Ethiopian Panel Data. *The Journal of Development Studies, 49*(7), 955–975. https://doi.org/10.1080/00220388.2013.785523

Labeyrie, V., Renard, D., Aumeeruddy-Thomas, Y., Benyei, P., Caillon, S., Calvet-Mir, L., Carriere, S. M., Demongeot, M., Descamps, E., Junqueira, A. B., Li, X., Locqueville, J., Mattalia, G., Minarro, S., Morel, A., Porcuna-Ferrer, A., Schlingmann, A., da Cunha Avila, J. V., & Reyes-Garcia, V. (2021). The role of crop diversity in climate change adaptation: Insights from local observations to inform decision making in agriculture. *Current Opinion In Environmental Sustainability, 51*, 15–23. https://doi.org/10.1016/j.cosust.2021.01.006

Lairez, J., Lopez-Ridaura, S., Jourdain, D., Falconnier, G. N., Lienhard, P., Striffler, B., Syfongxay, C., & Affholder, F. (2020). Context matters: Agronomic field monitoring and participatory research to identify criteria of farming system sustainability in South-East Asia. *Agricultural Systems, 182*, Article 102830. https://doi.org/10.1016/j.agsy.2020.102830

Lamichhane, P., Miller, K. K., Hadjikakou, M., & Bryan, B. A. (2020). Resilience of smallholder cropping to climatic variability. *Science of The Total Environment, 719*, Article 137464. https://doi.org/10.1016/j.scitotenv.2020.137464

Lee, D. R. (2005). Agricultural sustainability and technology adoption: Issues and policies for developing countries. *American Journal of Agricultural Economics, 87*(5), 1325–1334. https://doi.org/10.1111/j.1467-8276.2005.00826.x

Leroux, L., Faye, N. F., Jahel, C., Falconnier, G. N., Diouf, A. A., Ndao, B., Tiaw, I., Senghor, Y., Kanfany, G., Balde, A., Dieye, M., Sirdey, N., Alobo Loison, S., Corbeels, M., Baudron, F., & Bouquet, E. (2022). Exploring the agricultural landscape diversity-food security nexus: An analysis in two contrasted parklands of Central Senegal. *Agricultural Systems, 196*, Article 103312. https://doi.org/10.1016/j.agsy.2021.103312

Lien, G., Brian Hardaker, J., & Flaten, O. (2007). Risk and economic sustainability of crop farming systems. *Agricultural Systems, 94*(2), 541–552. https://doi.org/10.1016/j.agsy.2007.01.006

Lopez-Ridaura, S., Frelat, R., van Wijk, M. T., Valbuena, D., Krupnik, T. J., & Jat, M. L. (2018). Climate smart agriculture, farm household typologies and food security: An ex-ante assessment from Eastern India. *Agricultural Systems, 159*, 57–68. https://doi.org/10.1016/j.agsy.2017.09.007

Manda, J., Alene, A. D., Tufa, A. H., Abdoulaye, T., Kamara, A. Y., Olufajo, O., Boukar, O., & Manyong, V. M. (2020). Adoption and ex-post impacts of improved Cowpea varieties on productivity and net returns in Nigeria. *Journal of Agricultural Economics, 71*(1), 165–183. https://doi.org/10.1111/1477-9552.12331

Marandure, T., Mapiye, C., Makombe, G., & Dzama, K. (2017). Indicator-based sustainability assessment of the smallholder beef cattle production system in South Africa. *Agroecology and Sustainable Food Systems, 41*(1), 3–29. https://doi.org/10.1080/21683565.2016.1231152

Marenya, P. P., Gebremariam, G., Jaleta, M., & Rahut, D. B. (2020). Sustainable intensification among smallholder maize farmers in Ethiopia: Adoption and impacts under rainfall and unobserved heterogeneity. *Food Policy, 95*, Article 101941. https://doi.org/10.1016/j.foodpol.2020.101941

Mashingaidze, N., Belder, P., Twomlow, S., Hove, L., & Moyo, M. (2013). Improving maize (zea mays l.) Performance in semi-arid Zimbabwe through micro-dosing with ammonium nitrate tablets. *Experimental Agriculture, 49*(2), 179–196. https://doi.org/10.1017/S0014479712001020

Maxwell, D., & Caldwell, R. (2008). *The coping strategies index: Field methods manual.* Cooperative for Assistance and Relief Everywhere Inc. USA.

Maxwell, S., & Fernando, A. (1989). Cash crops in developing countries: The issues, the facts, the policies. *World Development, 17*(11), 1677–1708. https://doi.org/10.1016/0305-750X(89)90193-9

Medrano, H., Tomás, M., Martorell, S., Escalona, J.-M., Pou, A., Fuentes, S., Flexas, J., & Bota, J. (2015). Improving water use efficiency of vineyards in semi-arid regions. A review. *Agronomy for Sustainable Development, 35*(2), 499–517. https://doi.org/10.1007/s13593-014-0280-z

Mennig, P., & Sauer, J. (2020). The impact of agri-environment schemes on farm productivity: A DID-matching approach. *European Review of Agricultural Economics, 47*(3), 1045–1093. https://doi.org/10.1093/erae/jbz006

Mishra, A. K., Kumar, A., Joshi, P. K., & D'souza, A. (2016). Impact of contracts in high yielding varieties seed production on profits and yield: The case of Nepal. *Food Policy, 62*, 110–121. https://doi.org/10.1016/j.foodpol.2016.05.005

Moeller, C., Sauerborn, J., de Voil, P., Manschadi, A. M., Pala, M., & Meinke, H. (2014). Assessing the sustainability of wheat-based cropping systems using simulation modelling: Sustainability = 42? *Sustainability Science, 9*(1), 1–16. https://doi.org/10.1007/s11625-013-0228-2

Moraine, M., Duru, M., & Therond, O. (2017). A social-ecological framework for analyzing and designing integrated crop–livestock systems from farm to territory levels. *Renewable Agriculture and Food Systems*, *32*(1), 43–56. Cambridge Core. https://doi.org/10.1017/S1742170515000526.

Mrema, G. C., Kahan, D. G., & Agyei-Holmes, A. (2020). *Agricultural mechanization in Tanzania. An Evolving Paradigm of Agricultural Mechanization Development: How Much Can Africa Learn from Asia*, 457–496.

Muricho, D. N., Otieno, D. J., Oluoch-Kosura, W., & Jirström, M. (2019). Building pastoralists' resilience to shocks for sustainable disaster risk mitigation: Lessons from West Pokot County, Kenya. *International Journal of Disaster Risk Reduction, 34*, 429–435. https://doi.org/10.1016/j.ijdrr.2018.12.012

Mutyasira, V., Hoag, D., Pendell, D., Manning, D. T., & Berhe, M. (2018). Assessing the relative sustainability of smallholder farming systems in Ethiopian highlands. *Agricultural Systems, 167*, 83–91. https://doi.org/10.1016/j.agsy.2018.08.006

Mwinuka, L., Mutabazi, K. D., Graef, F., Sieber, S., Makindara, J., Kimaro, A., & Uckert, G. (2017). Simulated willingness of farmers to adopt fertilizer micro-dosing and rainwater harvesting technologies in semi-arid and sub-humid farming systems in Tanzania. *Food Security, 9*(6), 1237–1253. https://doi.org/10.1007/s12571-017-0691-1

Nakano, Y., Tanaka, Y., & Otsuka, K. (2018). Impact of training on the intensification of rice farming: Evidence from rainfed areas in Tanzania. *Agricultural Economics, 49*(2), 193–202. https://doi.org/10.1111/agec.12408

Negi, V. S., Maikhuri, R. K., Chandra, A., Maletha, A., & Dhyani, P. P. (2018). Assessing sustainability of farming systems in mountain agroecosystems of Western Himalaya, India. *Agroecology and Sustainable Food Systems, 42*(7), 751–776. https://doi.org/10.1080/21683565.2018.1427175

Nguyen Chau, T., & Scrimgeour, F. (2021). Productivity impacts of hybrid rice seeds in Vietnam. *Journal of Agricultural Economics, 00*, 1–16. https://doi.org/10.1111/1477-9552.12458

Onduru, D. D., & Du Preez, C. C. C. (2008). Farmers' knowledge and perceptions in assessing tropical dryland agricultural sustainability: Experiences from Mbeere District, Eastern Kenya. *International Journal of Sustainable Development & World Ecology, 15*(2), 145–152. https://doi.org/10.1080/13504500809469779

Ouedraogo, Y., Taonda, J.-B.-S., Sermé, I., Tychon, B., & Bielders, C. L. (2020). Factors driving cereal response to fertilizer microdosing in sub-Saharan Africa: A meta-analysis. *Agronomy Journal, 112*(4), 2418–2431. https://doi.org/10.1002/agj2.20229

Özerol, G., Bressers, H., & Coenen, F. (2012). Irrigated agriculture and environmental sustainability: An alignment perspective. *Environmental Science & Policy, 23*, 57–67. https://doi.org/10.1016/j.envsci.2012.07.015

Pan, Y., Smith, S. C., & Sulaiman, M. (2018). Agricultural extension and technology adoption for food security: Evidence from Uganda. *American Journal of Agricultural Economics, 100*(4), 1012–1031. https://doi.org/10.1093/ajae/aay012

Peralta, A., Swinton, S. M., & Jin, S. (2018). The secret to getting ahead is getting started: Early impacts of a rural development project. *Sustainability, 10*(8). https://doi.org/10.3390/su10082644

Pham, L. V., & Smith, C. (2013). Agricultural sustainability in developing countries: An assessment of the relationships between drivers and indicators in Hoa Binh Province, Vietnam. *Agroecology and Sustainable Food Systems, 37*(10), 1144–1186. https://doi.org/10.1080/21683565.2013.833153

Pretty, J., Peacock, J., Hine, R., Sellens, M., South, N., & Griffin, M. (2007). Green exercise in the UK countryside: Effects on health and psychological well-being, and implications for policy and planning. *Journal of Environmental Planning and Management, 50*(2), 211–231. https://doi.org/10.1080/09640560601156466

Pufahl, A., & Weiss, C. (2009). Evaluating the effects of farm programmes: Results from propensity score matching. *European Review of Agricultural Economics, 36*(1), 79–101.

Rao, N., & Rogers, P. (2006). Assessment of agricultural sustainability. *Current Science*, 439–448.

Renner, S., Sauer, J., & El Benni, N. (2021). Why considering technological heterogeneity is important for evaluating farm performance? *European Review of Agricultural Economics, 48*(2), 415–445. https://doi.org/10.1093/erae/jbab003

Ripoll-Bosch, R., Díez-Unquera, B., Ruiz, R., Villalba, D., Molina, E., Joy, M., Olaizola, A., & Bernués, A. (2012). An integrated sustainability assessment of mediterranean sheep farms with different degrees of intensification. *Agricultural Systems, 105*(1), 46–56. https://doi.org/10.1016/j.agsy.2011.10.003

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio, 46*(1), 4–17. https://doi.org/10.1007/s13280-016-0793-6

Rondhi, M., Pratiwi, P. A., Handini, V. T., Sunartomo, A. F., & Budiman, S. A. (2018). Agricultural land conversion, land economic value, and sustainable agriculture. A case study in East Java, Indonesia. *Land, 7*(4). https://doi.org/10.3390/land7040148

Rosenbaum, P. R. (2002). *Observational Studies*. Springer. https://books.google.nl/books?id=K0OglGXtpGMC.

Rosenbaum, P. R. (2007). Sensitivity analysis for m-estimates, tests, and confidence intervals in matched observational studies. *Biometrics, 63*(2), 456–464. https://doi.org/10.1111/j.1541-0420.2006.00717.x

Ruzzante, S., Labarta, R., & Bilton, A. (2021). Adoption of agricultural technology in the developing world: A meta-analysis of the empirical literature. *World Development, 146*, Article 105599. https://doi.org/10.1016/j.worlddev.2021.105599

Ryan, M., Hennessy, T., Buckley, C., Dillon, E., Donnellan, T., Hanrahan, K., & Moran, B. (2016). Developing farm-level sustainability indicators for Ireland using the Teagasc National Farm Survey. *Irish Journal of Agricultural and Food Research, 55*. https://doi.org/10.1515/ijafr-2016-0011

Saidia, P., Asch, F., Kimaro, A., Germer, J., Kahimba, F., Graef, F., Semoka, J., & Rweyemamu, C. (2019a). Data in brief on inter-row rainwater harvest and fertilizer application on yield of maize and pigeon-pea cropping systems in sub humid tropics. *Data in Brief, 26*, Article 104456. https://doi.org/10.1016/j.dib.2019.104456

Saidia, P., Asch, F., Kimaro, A., Germer, J., Kahimba, F., Graef, F., Semoka, J., & Rweyemamu, C. (2019b). Soil moisture management and fertilizer micro-dosing on yield and land utilization efficiency of inter-cropping maize-pigeon-pea in sub humid Tanzania. *Agricultural Water Management, 223*. https://doi.org/10.1016/j.agwat.2019.105712

Sanginga, N., & Woomer, P. L. (2009). *Integrated soil fertility management in Africa: Principles, practices, and developmental process*. CIAT.

Schindler, J., Graef, F., König, H. J., Mchau, D., Saidia, P., & Sieber, S. (2016). Sustainability impact assessment to improve food security of smallholders in Tanzania. *Environmental Impact Assessment Review, 60*, 52–63. https://doi.org/10.1016/j.eiar.2016.04.006

Shakya, B., Shrestha, A., Sharma, G., Gurung, T., Mihin, D., Yang, S., Jamir, A., Win, S., Han, X., Yang, Y., Choudhury, D., & Schneider, F. (2019). Visualizing sustainability of selective mountain farming systems from far-eastern Himalayas to support decision making. *Sustainability, 11*(6). https://doi.org/10.3390/su11061714

Shiferaw, B., Kassie, M., Jaleta, M., & Yirga, C. (2014). Adoption of improved wheat varieties and impacts on household food security in Ethiopia. *Food Policy, 44*, 272–284. https://doi.org/10.1016/j.foodpol.2013.09.012

Sieber, S., Graef, F., Amjath-Babu, T. S., Mutabazi, K. D., Tumbo, S. D., Faße, A., Gomez y Paloma, S., Rybak, C., Lana, M. A., Ndah, H. T., Uckert, G., Schuler, J., & Grote, U. (2018). Trans-SEC's food security research in Tanzania: From constraints to adoption for out- and upscaling of agricultural innovations. *Food Security, 10*(4), 775–783. https://doi.org/10.1007/s12571-018-0822-3

Silvestri, C., Silvestri, L., Piccarozzi, M., & Ruggieri, A. (2022). Toward a framework for selecting indicators of measuring sustainability and circular economy in the agri-food sector: A systematic literature review. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-022-02032-1

Simonet, G., Subervie, J., Ezzine-de-Blas, D., Cromberg, M., & Duchelle, A. E. (2019). Effectiveness of a REDD+ Project in Reducing Deforestation in the Brazilian Amazon. *American Journal of Agricultural Economics, 101*(1), 211–229. https://doi.org/10.1093/ajae/aay028

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1492), 789. https://doi.org/10.1098/rstb.2007.2184

Stathers, T., Holcroft, D., Kitinoja, L., Mvumi, B. M., English, A., Omotilewa, O., Kocher, M., Ault, J., & Torero, M. (2020). A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. *Nature Sustainability, 3*(10), 821–835. https://doi.org/10.1038/s41893-020-00622-1

Thierfelder, C., Paterson, E., Mwafulirwa, L., Daniell, T. J., Cairns, J. E., Mhlanga, B., & Baggs, E. M. (2022). Toward greater sustainability: How investing in soil health may enhance maize productivity in Southern Africa. *Renewable Agriculture and Food Systems, 37*(2), 166–177. Cambridge Core. https://doi.org/10.1017/S1742170521000442.

Tittonell, P. (2014). Livelihood strategies, resilience and transformability in African agroecosystems. *Designing Sustainable Agricultural Production Systems for a Changing World: Methods and Applications, 126*, 3–14. https://doi.org/10.1016/j.agsy.2013.10.010

Tittonell, P., & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Crop Yield Gap Analysis – Rationale, Methods and Applications, 143*, 76–90. https://doi.org/10.1016/j.fcr.2012.10.007

Tovihoudji, P. G., Akponikpè, P. B. I., Agbossou, E. K., Bertin, P., & Bielders, C. L. (2017). Fertilizer microdosing enhances maize yields but may exacerbate nutrient mining in maize cropping systems in northern Benin. *Field Crops Research, 213*, 130–142. https://doi.org/10.1016/j.fcr.2017.08.003

Udagawa, C., Hodge, I., & Reader, M. (2014). Farm level costs of agri-environment measures: The impact of entry level stewardship on cereal farm incomes. *Journal of Agricultural Economics, 65*(1), 212–233. https://doi.org/10.1111/1477-9552.12043

ul Haq, S., & Boz, I. (2018). Developing a set of indicators to measure sustainability of tea cultivating farms in Rize Province, Turkey. *Ecological Indicators, 95*, 219–232. https://doi.org/10.1016/j.ecolind.2018.07.041

Ulukan, D., Bergkvist, G., Lana, M., Fasse, A., Mager, G., Oborn, I., & Chopin, P. (2022). Combining sustainable livelihood and farm sustainability approaches to identify relevant intensification options: Implications for households with crop-based and gathering-based livelihood in Tanzania. *Ecological Indicators, 145*. https://doi.org/10.1016/j.ecolind.2022.109518

Vanham, D., & Bidoglio, G. (2013). A review on the indicator water footprint for the EU28. *Ecological Indicators, 26*, 61–75. https://doi.org/10.1016/j.ecolind.2012.10.021

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E. M. A., Woomer, P. L., & Sanginga, N. (2010). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture, 39*(1), 17–24. https://doi.org/10.5367/000000010791169998

Veisi, K., Bijani, M., & Abbasi, E. (2020). A human ecological analysis of water conflict in rural areas: Evidence from Iran. *Global Ecology and Conservation, 23*, e01050.

Vilei, S. (2011). Local perceptions of sustainability of farming systems on Leyte, Philippines – Divergences and congruencies between different stakeholders. *International Journal of Sustainable Development & World Ecology, 18*(4), 291–303. https://doi.org/10.1080/13504509.2011.555112

Viteri Salazar, O., Ramos-Martín, J., & Lomas, P. L. (2018). Livelihood sustainability assessment of coffee and cocoa producers in the Amazon region of Ecuador using household types. *Journal of Rural Studies, 62*, 1–9. https://doi.org/10.1016/j.jrurstud.2018.06.004

Wilkus, E., Roxburgh, C., & Rodriguez, D. (2019). *Understanding household diversity in rural eastern and southern Africa*. Australian Centre for International Agricultural Research: Canberra, ACT. 184 pp.

Winters, P., Maffioli, A., & Salazar, L. (2011). Introduction to the special feature: Evaluating the impact of agricultural projects in developing countries. *Journal of Agricultural Economics, 62*(2), 393–402. https://doi.org/10.1111/j.1477-9552.2011.00296.x

Wiesmann, D., Bassett, L., Benson, T., & Hoddinott, J. (2009). *Validation of the world food programme s food consumption score and alternative indicators of household food security*. Intl Food Policy Res Inst. IFPRI Discussion Paper 2009. 91.

Wiyo, K. A., Kasomekera, Z. M., & Feyen, J. (2000). Effect of tied-ridging on soil water status of a maize crop under Malawi conditions. *Agricultural Water Management, 45*(2), 101–125. https://doi.org/10.1016/S0378-3774(99)00103-1

World Bank. (2011). *Impact Evaluations in Agriculture: An Assessment of the Evidence* (Independent Evaluation Group). Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/27794.

Yegbemey, R. N., Yabi, J. A., Dossa, C. S. G., & Bauer, S. (2014). Novel participatory indicators of sustainability reveal weaknesses of maize cropping in Benin. *Agronomy for Sustainable Development, 34*(4), 909–920. https://doi.org/10.1007/s13593-014-0214-9

Yorobe, J. M., Jr., Ali, J., Pede, V. O., Rejesus, R. M., Velarde, O. P., & Wang, H. (2016). Yield and income effects of rice varieties with tolerance of multiple abiotic stresses: The case of green super rice (GSR) and flooding in the Philippines. *Agricultural Economics, 47*(3), 261–271. https://doi.org/10.1111/agec.12227

Zhang, B., Yan, S., Li, B., Wu, S., Feng, H., Gao, X., Song, X., & Siddique, K. H. M. (2023). Combining organic and chemical fertilizer plus water-saving system reduces environmental impacts and improves apple yield in rainfed apple orchards. *Agricultural Water Management, 288*, Article 108482. https://doi.org/10.1016/j.agwat.2023.108482