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# Combining sustainable livelihood and farm sustainability approaches to identify relevant intensification options: Implications for households with crop-based and gathering-based livelihoods in Tanzania

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ABSTRACT

In low-income countries, the livelihoods of smallholders are affected to different extent by multiple issues, such as food insecurity or low soil fertility, depending on their multiple assets and farming characteristics. In this study, we aim at assessing the current sustainability of households in Tanzania to suggest potential changes in farming system to increase the household sustainability. Household survey data from 891 households in two regions of Tanzania (dry Dodoma and humid Morogoro) were used to build composite sustainability indices representing the three pillars of sustainability (economic, environmental and social), based on 46 basic indicators. Then, a household typology was developed through principal component analysis and hierarchical clustering analysis of descriptive variables, and regression analysis linked the sustainability of farms with household characteristics. The analysis revealed significant differences in household types that relied on different livelihood strategies including particularly a "Gathering-based" type in Dodoma and two "Crop-based" types in both regions. These livelihoods significantly influenced the level of farming system sustainability. Particularly, the households in the "Gathering-based" type performed worst on all three pillars of sustainability. By examining the level of capitals from the different household types, we identified that the "Gathering-based" type and "Crop-based" types could improve their livelihood and be better off if they adopt various upgrading solutions. Such solutions include intercropping and optimised weeding to increase productivity and resource-use efficiency, for which these households have sufficient labour resources. Additionally, livestock rearing and use of fertilisers coupled with rainwater harvesting can increase soil fertility and water use efficiency, and hence food security, without compromising the environmental component of sustainability. To facilitate the adoption of these sustainable intensification options, agricultural policies and appropriate training need to be implemented to fit the local context and diversity of household types.

## 1. Introduction

Food insecurity, poverty and natural resources degradation are major obstacles to sustainable development in many low-income countries (Pravalie et al., 2021; Smith et al., 2017). Despite low-income economies mainly being based on agriculture and smallholder farmers providing most of the food, smallholder farmers are the population group most affected by food insecurity and poverty (Dethier and Effenberger, 2012; IFAD, UNED, 2013; Schindler et al., 2015). In Africa, 90% of agricultural products are supplied by farms with an average size of one hectare (IFAD, UNED, 2013). In Tanzania, local smallholder systems produce enough to meet 95% of national food requirements (Schindler et al., 2017). However, 49% of the Tanzanian population lives below the poverty line (World Bank, 2019) and 33% of the population was undernourished in 2011–2013. Smallholder farms, mainly rain-fed, face many constraints due to limited resources and capacity, a

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situation resulting in low agricultural productivity (Sieber et al., 2017; Suleiman et al., 2018). Inadequate infrastructure and storage, low economies of scales, lack of incentives (Sieber et al., 2017) and limited access to markets (Suleiman et al., 2018) are structural shortcomings in Tanzanian agri-food systems. The country is also experiencing rapid population growth, and thus available land per capita is shrinking (Graef et al., 2014; Uckert et al., 2018) and soil fertility is decreasing (Suleiman et al., 2018). Farming systems are intensifying to meet the increasing demand for food, feed and firewood further increasing the pressure on natural resources (Mnenwa and Maliti, 2010). Climate change, including increased frequency of droughts and intense rainfall events, and price volatility due to trade liberalisation are other large-scale factors shaping the present and future of agriculture and food security in Tanzania (Graef et al., 2014; Kangalawe and Lyimo, 2013; Müller, 2011; von Braun, 2008).

Sustainable intensification of agriculture is being promoted by development projects in sub-Saharan Africa seeking to address challenges related to food security while reducing the environmental impacts (Nziguheba et al., 2021). Pretty (1995) defined sustainable intensification as improving productivity while preserving or increasing natural resources, and later added that it should be based on use of natural, social and human capitals, combined with use of appropriate technologies (Pretty et al., 2008). In Tanzania, researchers have identified several sustainable intensification options of interest for households that could be implemented to increase food security especially at household level potentially using different types of resources or capitals (Graef et al., 2014). These sustainable intensification options, also called upgrading strategies, were designed to fit the diversity of the Tanzania agricultural systems and included for instance optimal weeding, rainwater harvesting or fertiliser micro-dosing (Sieber et al., 2017). Potential impacts of these strategies were assessed ex-ante using a limited number of participatory criteria (see Hernandez et al., 2019; Schindler et al., 2016). However, there is still a knowledge gap concerning the overall potential impact on sustainability of the range of farm households targeted and the potential of the strategies to achieve an increase in initial sustainability depending on the study area. This knowledge is of major importance in order to promote sustainable intensification options adapted for each type of household depending on their level of resources and possibilities to adopt them.

A great number of indicators have been used to assess the sustainability of farming systems, but its definition remains complex, controversial and subjective (Hayati et al., 2011). The site-specific and dynamic characteristics (changes over space and time) of agricultural sustainability make it difficult to formulate indices that are generally applicable (Ikerd, 1993). Empirical evaluations of sustainability can be conducted based on social constructs of sustainability and observed variations in the results of specific indicators (Gómez-Limón and Sanchez-Fernandez, 2010). According to Yegbemey et al., (2014), farm sustainability is "the capacity of a farming system to maintain or improve its economic viability over time before major disturbances such as land degradation and climate change occur, while respecting the environment and preserving social coordination". Farming systems are managed by humans and their characteristics and linked to household characteristics which also influences the subsequent sustainability of this system. The focus on household characteristics which are driving the characteristics of farming system seems to be the relevant scale to address change of impact of agricultural activities among smallholders (Chopin et al., 2021). A sustainable farming system ensures a balanced delivery of private and public goods maintained over time, so as to ensure economic, social, and environmental sustainability (El Ansari et al., 2020). This maintenance over time also means that sustainability of farming system encompass the resilience of the systems which is basically "the capacity of a social ecological system to deal with shocks" (Tittonell, 2014a), a concept mentioned in the United Nations Sustainable Development Goals (SDGs) for 2030 (Quandt, 2018). It is known that the adoption of new technology may vary among farm households because of differences in socio-economic characteristics. Typology development is a well-established means of describing heterogeneity amongst land managers (Mądry et al., 2013). A typology approach enables the design and implementation of interventions and policies that are tailored to the specificities of different and distinct characteristics (Lopez-Ridaura et al., 2018; Tittonell, 2014a). Hence linking typology of household with farming system sustainability and impact can help finding tangible measures of increased sustainability and resilience of household (Ansah et al., 2019).

In practice, there are many agricultural sustainability assessment tools and frameworks that have been produced at the household and farm level, such as IDEA, SAFE and RISE (Chopin et al. 2021). However, these approaches focus on externalities of farming systems in terms of income produced, use of resources and environmental impacts, without accounting for the household-specific drivers or characteristics that explain the overall performance of the farming system. The sustainable livelihood approach (SLA) has been applied in the field of international development to assess household sustainability (Paul et al., 2020; Wang et al., 2016). This approach is based on assessment of five categories of capital (financial, physical, natural, human and social) (Quandt, 2018) and provides a holistic evaluation going beyond the farm and including the household. In SLA, assets are considered direct drivers of sustainability, rather than farming practices and farming systems externalities, which are not covered by the indicators used for different types of capital. Chopin et al. (2021) reviewed 119 tools to address farming system sustainability and found that household sustainability assessment via SLA was disconnected from approaches of sustainability assessment of farming system impact using economic, social and environmental indicators. This disconnection between SLA and sustainability assessment of farming system may prevent the identification of relevant farming practices (i.e., sustainable intensification options) that are i) tailored to the resources of households in terms of capital and that ii) can subsequently increase the sustainability of the farming system. The authors also pointed out the lack of assessment of some system properties such as resilience of farming system, which is of major importance for sustainability of households and generally poorly addressed. These systems properties assessed via indicators offer an opportunity to capture the variability of impacts that farming systems can have based on data collected only for one year (Hossard et al., 2021).

In this study, we develop an innovative approach combining SLA and farm sustainability assessment to i) gain a better understanding of the drivers of sustainability and to ii) identify sustainable intensification options in order to improve livelihoods tailored to different households in contrasted biophysical contexts. Our research question is 'How does the variability of household livelihoods drive the sustainability of farming systems and the sub-sequent recommendations in terms of options to improve the performance of these farming systems?'. We hypothesize that the households that have the lowest level of capital have the least sustainable farming systems and that recommendations to increase sustainability are specific to each type of household. Specific objectives of the work were to: (1) Develop a set of composite indices (based on basic indicators) reflecting site-specific features of the study area to capture the environmental, economic and social dimensions of farm household sustainability and its resilience to climate change, (2) to group farm households according to their variability in terms of household assets and farm characteristics, and (3) to relate the variation in sustainability to household and farm characteristics.

## 2. Materials and methods

### 2.1. Study area

The research project was conducted in two regions of Tanzania, Morogoro and Dodoma (Fig. 1), since most agricultural systems found in Tanzania are represented in these regions which have very contrasted biophysical and socioeconomic characteristics. The results of farming

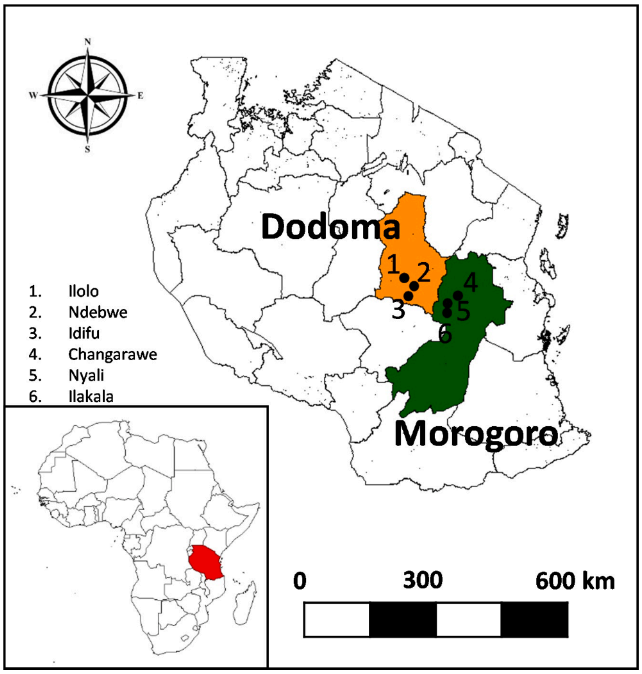


**Fig. 1.** Map of Tanzania showing the two study regions, Morogoro and Dodoma. Source: trans-*SEC* project.

system sustainability analysis can be extrapolated to other regions of Tanzania. Dodoma has a flat landscape with loamy sand soils and a semi-arid climate (~500 mm annual rainfall), while Morogoro is characterised by loamy soils, a more diverse landscape and a sub-humid climate (~900 mm annual rainfall) (Mnenwa and Maliti, 2010). The two regions also differ socio-economically, as farms in Morogoro have better access to machinery, infrastructure and market, and growth stunting in children is less common (Uckert et al., 2018). Regional agricultural production is more diverse in Morogoro but only partly integrated with livestock, while agriculture in Dodoma is characterised by production of sorghum and millet in combination with livestock (Mnenwa and Maliti, 2010). The two regions represent central and coastal areas of Tanzania and have the highest rural population in Tanzania, whose main occupation is agriculture according to the 2012 census report (National Bureau of Statistics, Office of Chief Government Statistician, 2014). These two regions were selected because they have a diverse set of socio-economic and agro-ecological conditions for analysis (Graef et al., 2014), they represent contrasting food systems (Reincke et al., 2018) and cover the majority of farming systems (70%–80%) in Tanzania (Graef et al., 2014).

For this study, sampling consisted of 3 villages in each region aiming at having comparable and simultaneously diverse conditions, including the presence of varied degrees of market access (not every village includes a marketplace), similar climatic conditions by district, rain-fed cropping systems, livestock integration, and relatively similar village sizes (800–1500 households) (Graef et al., 2014). The study covered six villages; Nyali, Changarawe and Ilakala in Kilosa district and Ilolo, Ndebwe and Idifu in Chamwino district. For the survey, household lists were prepared in collaboration with village authorities for each of the six villages and households were then randomly selected. A total of 900 households (150 households in each village) were surveyed using a structured questionnaire with detailed sections on household socio-demographics, agriculture, marketing, non-farm activities and food security. Crops differ between the villages and regions depending on local conditions (Kissoly et al., 2020). In general, the first farming activity starts in September at the earliest, with the preparation of the fields. The last activity ends by August of the following year, with the harvest, processing and storage/marketing of the final crops (for example storing bulrush millet in Dodoma region and harvesting cotton in Morogoro).

### 2.2. Methodological framework

The methodological framework developed in this study encompasses various steps including data collection (2.2.1), sustainability assessment (2.2.2), farm household typology (2.2.3), calculation of composite indexes (2.2.4) and statistical analysis to identify determinants of sustainability (2.2.5) (Fig. 2). Data collection includes the collection of relevant information regarding the household characteristics, farming system and associated performance. The sustainability assessment is based on the calculation of relevant indicators capturing the sustainability of the farming system based on the environmental, economic and social dimensions and their associated components. The typology aims at grouping households based on the similarity of their characteristics to make relevant recommendations for a significant number of households for each regions. The composite indicators are built to identify which dimensions and components are currently weak and would be affected by appropriate interventions. Finally, a regression analysis allows to identify which characteristics in the household explain the sustainability levels and then drive the type of interventions that can be made to reverse the negative impacts of farming systems.

#### 2.2.1. Data collection

In 2014, 448 households in Dodoma and 443 in Morogoro were surveyed through face-to-face interviews. Household heads answered questions in an extensive questionnaire regarding the household situation over the period January 2013-December 2013. Questions were related to the variation in households̓ characteristics (e.g., migration) and outcomes of farming system (variation in productivity and food security) during the period 2008–2013. The questionnaire covered household structure, including age and education, household finance via information on assets, expenses, savings, loans and shock impacts, networks of relationships and information, and origin of income including non-agricultural sources such as off-farm employment, self-employment, fishing, hunting, collecting, logging, public transfers and aid and remittances. Water and energy consumption were recorded for each type of source. At field level, household head described land use for each plot, including distance to homestead and tenure. Crop management for each plot was recorded and contained information on e.g. planting (material, tillage), fertilisation and soil fertility management and harvesting (date, yield and losses). Livestock characteristics and management was recorded. Information was obtained on processing, consumption and sales of each product at household level as well as spending on food and healthcare. More information on the context is available in Supplementary Material 1.

#### 2.2.2. Sustainability assessment framework and indicator selection

An indicator-based framework was used for assessing farm household sustainability (Fig. 2). The spatial scale of analysis was the farm household and the temporal scale was one year, with a few exceptions depending on the nature of the indicator. The assessment was based on existing literature and survey data. First, each dimension of sustainability (social, economic, environmental) was broken down into components (Table 1). These components were defined using the approach of ul Haq and Boz (2018), who highlighted the importance of considering key site-specific features in sustainability assessments. Potential indicators that could bring information on the components of sustainability and that were validated in the literature on sustainable intensification were selected for this study and calculated following recommendations by Bockstaller et al. (2008). One or more indicators were associated with each component. Variables used in indicator calculations were either continuous or binary. Categorical variables from the survey were converted to binary variables. To obtain summary statistics, 'yes' values of binary indicators were converted to 1 and 'no' values to 0. Indicators can be quantitatively calculated on the basis of

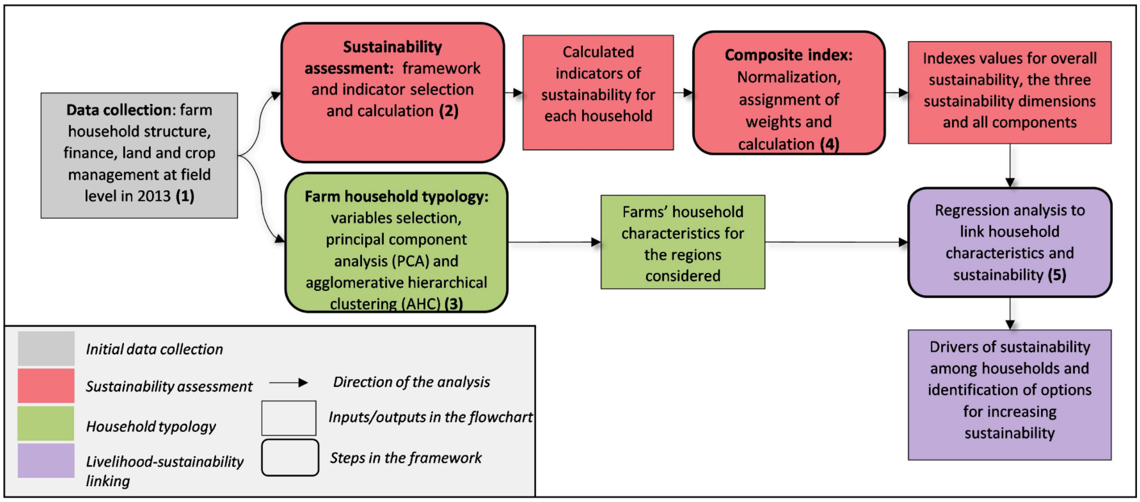


**Fig. 2.** Flowchart of our novel method combining sustainability assessment at farm level and household typology analysis based on variables used in the sustainable livelihood approach (SLA). The method was applied to assess the sustainability of farm households in the study regions in Tanzania and to identify options for sustainable intensification.

declared values or can be based on farmers' perceptions. We did not conduct direct measurements of environmental indicators, but recorded perceptions on the state of resources. We briefly explain the chosen indicators in Table 1 and provide more details in the Supplementary material 2 and their calculations for both regions.

### 2.2.3. *Farm household typology*

A farm household typology was created for each region, Morogoro and Dodoma, to better understand the variation among households in terms of human, natural, financial, physical capital following the principles of SLA. Human capital encompassed the household structure variable, including education, labour and household structure. Natural capital was represented by farm size, tenure, proportion of land use types and livestock. Financial capital was described by livelihood strategy variables, such as proportion of income from various activities and money flows within the household, including loans and food expenditures. Physical capital was the pure value of assets from the households and in terms of production. Social capital was not considered as it overlapped with the social sustainability of the sustainability assessment. A multivariate analysis was conducted using principal component analysis (PCA) which is a data reduction method that derives a smaller set of non-correlated dimensions from an initial set of quantitative variables, thus reducing the number of variables while preserving the variability in the dataset (Alvarez et al., 2018). The selected variables were checked for multi-collinearity. When two variables had Pearson correlation coefficient with an absolute value greater than 0.5 and reflected similar information, only one was considered for analysis (Köbrich et al., 2003). As a result, 27 variables of capitals were included in the analysis. Principal components with eigenvalue above 1 were selected, following the Kaiser criterion (Kuivanen et al., 2016). Then, the selected principal components were used in an agglomerative hierarchical classification (AHC) to group farm households, using the FactoMineR package in R (Husson et al., 2015). We used the Ward's minimum-variance method to select the best number of households types (Blazy et al., 2009; Chopin et al., 2015; Stylianou et al., 2020). The Ward's minimum-variance method progressively aggregates individuals to minimizes the intra-group variability and maximize the inter-group variability. The method then produce automatically an optimal typology of the population. The final step was to characterise distinct household types, highlight productive opportunities and constraints, and measure their level of dissimilarity using a Kruskal-Wallis test.

### 2.2.4. *Calculation of composite sustainability indices*

Composite indicators are calculated because they facilitate the targeting of innovations to improve the overall sustainability of farming systems. Indeed, they facilitate this process because i) they help summarise complex or multi-dimensional issues linked to agriculture, ii) they allow benchmarking performance of different farm household, iii) they facilitate judgments to be made on farm household sustainability and iv) they indicate which household represent the priority for improvement efforts. Based on selected sustainability indicators, composite sustainability indices were developed for each region. This was done in three steps: normalisation of data, assignment of weights and aggregation of data. Prior to analysis, continuous variables were treated for any missing or extreme values. Missing values were completed using impute PCA function Factominer package in R (Husson et al., 2015), which predicts missing values based on the correlation with all other variables of the dataset of indicators. The number of value imputed with the function was on average 5 values per indicator. The rational for this was to account for all households rather than removing households in the analysis for which one indicator would be missing out of 46 indicators.

In the data normalisation step, the basic indicators were normalised. This resulted in homogeneous units, which made it possible to compare indicators and perform arithmetic operations on them (Haileslassie et al., 2016; Mutyasira et al., 2018). The min–max normalisation technique was used (see (Gómez-Limón and Sanchez-Fernandez, 2010; Haileslassie et al., 2016; Mutyasira et al., 2018; Westers et al., 2017; Gómez-Limón and Sanchez-Fernandez, 2010; Haileslassie et al., 2016; Mutyasira et al., 2018). The output was an indicator varying within a dimensionless range [0, 1], where 0 was the observed minimum (i.e. least sustainable) and 1 the best (i.e. most sustainable) in that region. In the assignment of weights step, binary indicators were assigned half the weight of continuous indicators, a decision justified by the lower definition of information provided by binary indicators (Chopin et al., 2019). The weights of indicators vary depending on the number of indicators per component. If two indicators are used for one component, they would receive each a weight of 0.5 whilst for a component with four indicators, each indicator would receive a weight of 0.25. This difference has no impact on the analysis as indicators are not compared between the components. Only the components, which are all weighted equally within the same dimensions, are compared within a dimension.

Finally, the weighted indicators were aggregated by sustainability component. The aggregation rule applied to the set of normalised indicators was the weighted sum of indicators:

**Table 1**
Summary description of sustainability indicators.

| Pillar | Component | Indicators | Units | Reference of use |
|---|---|---|---|---|
| Social | Food security | Potential Food Availability index (PFAI) | (ratio) | (Frelat et al., 2015) |
| | | Food Consumption Score (FCS) | (score) | (Jones et al., 2013a) |
| | | Coping Strategies Index (CSI) at pre-harvest season | (score) | Jones et al. (2013) |
| | | Months of inadequate food provisioning | Number of months | (Lovon and Mathiassen, 2014) |
| | Health | Proportion of healthy household members | % of people | Marandure et al., (2017) |
| | | Health insurance status of the household | (yes/no) | ul Haq & Boz, (2018) |
| | Wellbeing | Workload of working household members | Hours/ active member | Antunes et al. (2017); Firbank et al. (2018) |
| | | Perceived deterioration in household wealth compared with the previous year | (yes/no) | Ripoll-Bosch et al. (2012) |
| | | High impact of income fluctuations on wellbeing | (yes/no) | Angelsen & Dokken (2018) |
| | Social capital | Agricultural information network | Number of sources | Hoang et al. (2006); Pretty et al. (2007) |
| | | Participation in farmers' group | (yes/no) | Mutyasira et al. (2018); Pretty et al. (2007) |
| | Land security | Farmer-perceived land security (proportion of land reported as secure by households) | % of area | Clover & Eriksen (2009); Shakya et al. (2019) |
| | | Land title ownership (proportion of land for which households had a written certificate) | % of area | Shakya et al. (2019) |
| | | Ability to pass on land to relatives | (yes/no) | Shakya et al. (2019) |
| | | Land use conflict | % of area | Shakya et al. (2019) |
| Econ-omic | Crop profitability | Average crop gross margin per hectare | US$/ha | (Antunes et al., 2017) |
| | | Average crop expenditure per hectare | US$/ha | (Viteri Salazar et al., 2018) |
| | | Labour productivity (the monetary value of crop produced per person and day) | US $/person | (Bernués et al., 2011) |
| | | Post-harvest loss (Average of the ratio of crop production lost after harvest for each crop) | % of amount | (Anriquez et al., 2021) |
| | Profitability | Net household income (crops, livestock, off-farm and self-employment, hunting, gathering, remittances and public transfers) | US $/year | (Kansiime et al., 2018) |
| | Stability | Decreasing yields | (yes/no) | (Poudel et al., 2017) |
| | | High income fluctuation | (yes/no) | (Haq and Boz, 2018) |
| | | Savings | (yes/no) | (Gikonyo et al., 2022) |
| | Vulnerability to shocks | Perceived high severity of shock | (yes/no) | (Baccar et al., 2019) |
| | | Amount of income loss due to shocks over the past five years | US$ | (Baccar et al., 2019) |
| | | Number of months needed to recover after shocks | Number of months | (Muricho et al., 2019) |
| Environmental | Soil management | Quantity of bought fertiliser | kg/ha | (Mutyasira et al., 2018) |
| | | Quantity of animal manure | kg/ha | (Negi et al., 2018) |
| | | Proportion of crop area perceived as infertile | % of area | (Asminaya et al., 2018) |
| | | Proportion of crop area with perceived decrease in fertility | % of area | (Onduru and Preez, 2008) |
| | | Proportion of crop area under legumes | % of area | (Moraine et al., 2017) |
| | | Proportion of crop area with residues left on the field | % of area | (Wilkus et al., 2019) |
| | | Proportion of area with intent to invest in soil fertility | % of area | (Lairez et al., 2020) |
| | | Tree density on agricultural land | Number of trees/ ha | (Yegbemey et al., 2014) |
| | | Area under erosion control measures (tree planting, terracing, grass strips and contouring) | % of area | (Mutyasira et al., 2018) |
| | Water management | Presence of irrigation | (yes/no) | Özerol et al. (2012) |
| | | Water use efficiency (crop production per ha and per mm of cumulative | kg/ha/ mm of rainfall | Medrano et al. (2015) |

(continued on next page)

 

**Table 1** (*continued*)

| Pillar | Component | Indicators | Units | Reference of use |
|---|---|---|---|---|
| | | annual rainfall for the region) | | |
| | | Good quality water consumption | % of amount | (Vanham and Bidoglio, 2013) |
| | | Decrease in water quality consumed in the households | % of amount | (Vanham and Bidoglio, 2013) |
| | | Household groundwater consumption for all activities | Litres/ capita | (Gerrard et al., 2012) |
| | | Change in water consumption | Litres | Abu-Bakar et al. (2021); Vanham & Bidoglio, (2013) |
| | | Water harvesting | (yes/no) | Gerrard et al. (2011) |
| | | Water use conflict reported by household members | % of amount | Veisi et al. (2020) |
| | Agricultural diversity | Crop diversity on the farm | Number of species | Fadul-Pacheco et al. (2013); Gaviglio et al., 2017) |
| | | Tree diversity on the farm | Number of species | Fadul-Pacheco et al. (2013); Gaviglio et al., 2017) |
| | | Livestock diversity on the farm | Number of species | Fadul-Pacheco et al. (2013); Gaviglio et al. (2017) |

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

where CI is composite sustainability component index, n is number of indicators for that component, w is weight assigned to the indicator and xnorm is the normalised indicator. This is an additive linear method that allows compensation among indicators.

Sustainability component indices were themselves aggregated into sustainability dimension indices. Despite the fact that we aggregate the sustainability of household into an index, all the dimensions and components of sustainability are examined separately. Hence, to avoid unbalanced results towards one given component or dimension, we applied equal weights to all components in a given dimension and each dimension (environmental, social and economy) received an equal weight of 0.33, which is recommended as standard (Babbie, 1995). The composite indices were then compared for different farm household types.

#### 2.2.5. *Determinants of sustainability indices*

Three multiple linear regressions were run in each region to explain sustainability scores (Fig. 2). The aim was to explain the sustainability performance for each pillar of sustainability based on structural and functional characteristics of farm households. The response variable (economic, environmental or social sustainability index) was explained by the variables used in typology construction. To validate the models built, normality of residuals was checked using the Shapiro-Wilk normality test. This test quantifies the relationship between the response variable and the explanatory variables, and indicates whether some explanatory variables have a relationship with the response variable. Independent variables explained a small part of the variations in sustainability pillar values, with adjusted $R^2$ ranging between 0.10 and 0.29.

## 3. Results

### 3.1. *Description of farm household types*

In Dodoma, 114 out of 448 households (25% of households surveyed in Dodoma) were found to be small, subsistence-oriented farms mainly relying on wood and leaf gathering for their livelihood (hereafter referred to as "Gathering based"), 221 households (49%) were small subsistence-oriented farms mainly relying on crops ("Crop based"), 88 households (20%) were medium subsistence and market-oriented farms mainly relying on livestock ("Livestock based"), and 25 households surveys (6% of our sample) were medium subsistence and market-oriented farms mainly relying on self-employment ("Self-employment based"). (Table 2, Fig. 3A, C). In the following paragraphs, these farm household types are respectively referred to as "Gathering-based", "Crop-based", "Livestock-based" and "Self-employment based" households and compared on the basis of their characteristics that vary between types.

Human capital showed differences in Dodoma as the "Gathering-based" households had on average household heads with lower education levels and less labour investment compared to other households (Table 3). The labour investment was greater for "Livestock-based" and "Self-employment-based" households with 766 and 637 $h.ha^{-1}$ in average respectively compared to 411 and 551 $h.ha^{-1}$ for the "Gathering-based" and "Crop-based" households. In terms of labour, the "Self-employment based" households had a higher proportion of hired labour with 32% compared to 5% in average for the three other types. For natural capital, households in the "Gathering-based" and "Crop-based" types had significantly less land (around 2 ha on average) than the "Livestock-based" and "Self-employment-based" households (around 4 ha on average). The "Gathering-based" and "Crop-Based" households had significantly less livestock, with 0.3 and 0.5 cattle herd in average per household in these two types compared to 2.6 and 3 cattle herds for the "Livestock-based" and "Self-employment-based" types respectively. "Livestock-based" households used more inputs than the other types. "Livestock-based" and "Self-employment-based" types grew cash crops on a larger proportion of their area than "Gathering-based" and "Crop-based" types. "Crop-based" and "Livestock-based" types grew more legumes than "Gathering-based" households. "Livestock-based" and "Self-employment-based" types had significantly more livestock (cattle, small ruminants and poultry) than "Gathering-based" and "Crop-based" types. In terms of financial capital, households in the "Gathering-based" type had a lower market orientation with only 3% of production sold compared to "Crop-based" (10%), "Livestock-based" (25%) and the "Self-employment-based" households (19%). In terms of physical capital, "Livestock-based" households were significantly more productive and had larger household assets than "Gathering-based" and "Crop-based" types, while "Self-employment-based" households were more productive and had larger assets than all other types. "Gathering-based" households spent the smallest amount of money on food.

In Morogoro, 165 households surveyed (37% of households surveyed in Morogoro) were small (<2 ha) subsistence and market-oriented farms relying on crops, livestock and off-farm activities (firewood gathering, fishing, and self-employment) ("Multi-activity-based"), 262 households (59% of the sample) were small market-oriented farms mostly relying on crops ("Crop-based"), and only 16 households (4% of our sample) were small market-oriented farms mainly relying on crops and livestock ("Crop-livestock-based") (Table 2, Fig. 3B, 3D). In the following paragraphs, these farm household types are referred to as "Multi-activity-based", "Crop-based", and "Crop-livestock-based" households, respectively.

For human capital, household heads in "Multi-activity-based"

**Table 2**

Farm household characteristics and average values of components of sustainability for the different household types in Dodoma and Morogoro. Mean and standard deviation (SD) are given for each variable.

| | | Dodoma | | | | | Morogoro | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Household types in the region | | All | Gathering-based | Crop-based | Livestock-based | Self-employment-based | All | Multi-activity-based | Crop-based | Crop-livestock-based |
| | Number of households (n) | 448 | 114 | 221 | 88 | 25 | 443 | 165 | 262 | 16 |
| Human capital | Household size (people) | 5.3 (2.2) | 4.5 (2) | 5.5 (2.1) | 5.6 (2.5) | 5.6 (2) | 4.4 (2.2) | 3.7 (2.1) | 4.8 (2.3) | 5.4 (1.5) |
| | Age of household head (years) | 49 (17) | 49 (17) | 50 (17) | 48 (16) | 41 (13) | 48 (36) | 54 (19) | 44 (15) | 42 (12) |
| | Education of household head (years) | 4.2 (3.3) | 3.0 (3.3) | 4.2 (3.2) | 4.6 (3.3) | 8.0 (2.3) | 4.9 (3.2) | 4.0 (3.5) | 5.5 (3) | 5.4 (3.4) |
| | Labour investment (h/ha) | 562 (748) | 411 (335) | 551 (593) | 766 (1260) | 637 (811) | 653 (738) | 694 (978) | 612 (499) | 935 (1046) |
| | Hired labour (%) | 5 (14) | 6 (15) | 1 (5) | 7 (14) | 32 (31) | 16 (26) | 14 (23) | 15 (25) | 57 (32) |
| Natural capital | Land size (ha) | 2.4 (2.4) | 1.7 (1) | 2.1 (1.3) | 3.6 (4.1) | 4.4 (4.1) | 2.1 (1.9) | 1.5 (1.1) | 2.5 (2.3) | 2.6 (1.4) |
| | Rented land (%) | 8 (21) | 15 (31) | 3 (15) | 12 (26) | 1 (6) | 17 (33) | 17 (33) | 16 (33) | 36 (42) |
| | Remote fields (%) | 35 (40) | 49 (43) | 27 (39) | 36 (38) | 47 (40) | 28 (43) | 28 (43) | 28 (42) | 29 (44) |
| | Distance to water (min) | 31 (34) | 29 (26) | 30 (37) | 41 (44) | 21 (16) | 28 (31) | 30 (32) | 27 (31) | 26 (22) |
| | Cash crop fields (%) | 11 (22) | 12 (18) | 7 (13) | 19 (19) | 22 (20) | 23 (26) | 9 (16) | 32 (27) | 11 (18) |
| | Legume fields (%) | 26 (20) | 20 (21) | 26 (21) | 31 (16) | 27 (17) | 6 (13) | 9 (16) | 4 (12) | 3 (6) |
| | Fruit & vegetable fields (%) | 1 (6) | 0 (2) | 1 (8) | 1 (4) | 2 (6) | 3 (8) | 2 (9) | 2 (6) | 35 (37) |
| | Fertiliser & pesticide costs (USD/ha) | 2.8 (11) | 0.4 (2) | 1.5 (6) | 9 (21) | 2 (7) | 13 (78) | 4 (12) | 5 (12) | 228 (352) |
| | Size of poultry flock | 0.0 (0.1) | 0 (0) | 0 (0.1) | 0.1 (0.1) | 0.1 (0.1) | 0.1 (0.2) | 0.1 (0.2) | 0.1 (0.1) | 0.1 (0.1) |
| | Size of pig herd | 0.1 (0.2) | 0.1 (0.2) | 0.1 (0.2) | 0.1 (0.2) | 0.3 (0.5) | 0.0 (0.1) | 0 (0.1) | 0 (0.1) | 0.1 (0.3) |
| | Size of cattle herd | 1.0 (2.3) | 0.3 (0.9) | 0.5 (1.4) | 2.6 (3.6) | 3 (3.5) | 0.4 (1.4) | 0.1 (0.7) | 0.2 (1.9) | 0.3 (1.1) |
| Financial capital | Crop production sold (%) | 11 (18) | 3 (8) | 10 (14) | 25 (25) | 19 (28) | 44 (27) | 28 (25) | 53 (23) | 65 (29) |
| | Crop income (%) | 33 (31) | 13 (16) | 50 (32) | 23 (24) | 14 (14) | 60 (32) | 31 (21) | 79 (19) | 44 (41) |
| | Livestock income (%) | 17 (27) | 6 (15) | 6 (13) | 57 (29) | 19 (30) | 12 (21) | 20 (28) | 7 (11) | 25 (33) |
| | Off-farm employment income (%) | 10 (21) | 9 (18) | 14 (25) | 3 (12) | 2 (10) | 4 (14) | 8 (20) | 2 (7) | 1 (6) |
| | Self-employment income (%) | 12 (23) | 7 (17) | 13 (23) | 4 (13) | 46 (38) | 6 (19) | 11 (26) | 3 (11) | 13 (27) |
| | Hunting&gathering income (%) | 24 (27) | 58 (28) | 13 (15) | 11 (12) | 13 (18) | 13 (19) | 22 (26) | 7 (10) | 9 (16) |
| | Public transfers&aid income (%) | 2 (5) | 4 (11) | 1 (3) | 0 (2) | 1 (4) | 0 (2) | 0 (5) | 0 (0) | 0 (0) |
| | Loans (USD) | 33 (50) | 18 (61) | 12 (46) | 28 (96) | 315 (581) | 50 (466) | 12 (49) | 19 (99) | 966 (2300) |
| | Food expenditure (USD) | 855 (680) | 649 (492) | 889 (728) | 917 (776) | 1276 (777) | 968 (790) | 786 (664) | 947 (797) | 3183(1961) |
| Physical capital | Productive assets (USD) | 73 (162) | 39 (62) | 48 (86) | 113 (132) | 314 (510) | 30 (63) | 18 (24) | 23 (23) | 257(210) |
| | Household assets (USD) | 332 (195) | 778 (152) | 79 (135) | 179 (215) | 1072 (862) | 207 (359) | 127 (252) | 212 (389) | 954 (959) |

households were older and less educated than those in "Crop-based" and "Crop-livestock-based" types. "Crop-livestock-based" households had a significantly more important investment in labour with 935 $h.ha^{-1}$ compared to the other two types along with a higher proportion of hired labour with 57% compared to 15% for the two other types. In terms of natural capital, the area managed by "Crop-based" households was significantly larger than for the "Multi-activity-based" type. "Crop-based" households grew more cash crops and legumes in terms of proportion of area than the other two farm types. "Crop-livestock-based" households grew more fruits and vegetables and spent more on inputs. For financial capital, "Crop-livestock-based" households had significantly more loans and spent significantly more on food than "Multi-activity-based" and "Crop-based" households. While "Crop-based" households had mostly their income from crops (79%), "Multi-activity-based" had income from not only crops with 31% of total income, but also livestock (20%) and hunting and gathering (22%). For physical capital, "Crop-livestock-based" households had significantly more assets than "Multi-activity-based" and "Crop-based" types. Assets for "Crop-based" households were slightly higher than for the "Multi-activity-based" households.

In both regions, the types revealed a difference between a majority of households with less natural and financial capital, and households with higher level of capitals representing a small part of the population. Moreover, gathering based households tended to rely more on off-farm income. In both Morogoro and Dodoma, a large type of "Crop-based" households, represented smallholders relying mostly on their own crop production. However, the reliance on crop income was greater in Morogoro and the reliance on incomes from off-farm activities was greater in Dodoma.

### 3.2. *Relative sustainability of farm household types*

The composite indices revealed significant differences between farm household types in both regions, with an overall higher sustainability score for the households with higher level of capitals represented by the "Livestock-based" and "Self-employment-based" types in Dodoma, and higher economic and social sustainability score for the "Crop-based " and "Crop-livestock-based" types in Morogoro (Table 3).

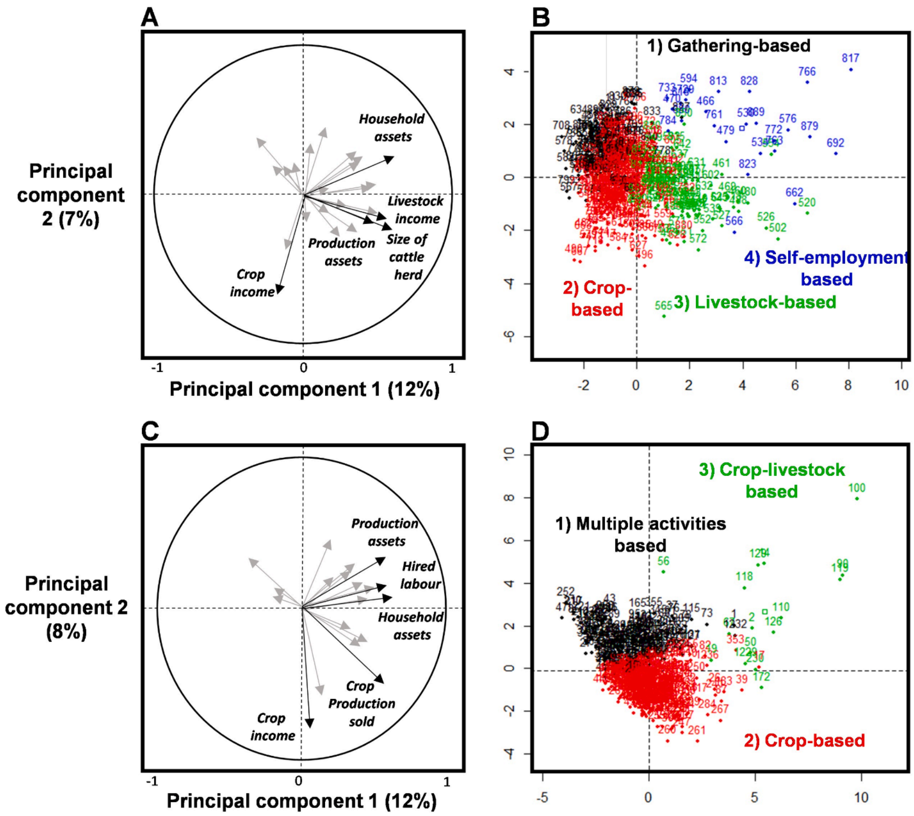


**Fig. 3.** Principal component analysis biplots for (A) Dodoma and (C) Morogoro: arrows indicate correlation of a parameter with the principal components (bottom and left axes, percentages refer to the variability explained by the principal component with the five most contributing variables shown as black arrows and labelled, while other variables are represented in grey. Results of agglomerative hierarchical classification (AHC) analysis performed on the principal components of the PCA for (B) the four types in Dodoma (with 7 components) used for classification, and (D) the three types in Morogoro (with 6 components used).

In Dodoma, the “Gathering-based” households showed the weakest performance on all dimensions, followed by the “Crop-based” households (Table 3). The “Livestock-based” type and “Self-Employment” type have similar environmental and economic indices but the “Self-employment” type has a higher value for the social index. The “Gathering-based” type showed the weakest performance for all environmental components except water management, for which the “Livestock-based” and “Self-employment-based” types showed poor performance. The “Livestock-based” households had significantly higher scores than the “Gathering-based” and “Crop-based” types for soil management. The “Livestock-based” and “Self-employment-based” types had the highest diversity scores, while the “Crop-based” households showed significantly more diversity than the “Gathering-based” type. As expected, the “Crop-based” type performed best in cropping activities, and also performed better in overall profitability than the “Gathering-based” type. However, the “Livestock-based” and “Self-employment-based” types surpassed both. Concerning economic stability and vulnerability to shocks, no significant difference was observed between the types. Concerning the social dimension, only the components food security and social capital varied significantly among households, with the “Gathering-based” type having the lowest scores for food security and social capital. The “Crop-based” type had comparable scores as the “Gathering-based” type except for the food security component for which “Crop-based” households scored significantly higher. The “Self-employment-based” type had significantly higher social capital score than the other types. There were no significant differences in health, wellbeing and land security scores across household types in Dodoma.

In Morogoro, households belonging to the “Multi-activity-based” type showed the poorest performance in all three sustainability dimensions followed by the “Crop-livestock based” and the “Crop-based” types. For the environmental dimension, there were no significant differences in soil and diversity scores between household types (Table 3). The “Crop-based” households performed significantly better than the “Multi-activity-based” type in water management. For the economy dimension, the “Crop-based” type was significantly better than other types when it came to crop performance, whereas the “Multi-activity-based” type showed the lowest overall household profitability and economic stability among household types. The “Multi-activity-based” and “Crop-based” types showed lower vulnerability to shocks than the “Crop-livestock-based” type. The “Crop-livestock-based” type had the highest profitability score compared to the two other types. For the social dimension, the “Crop-livestock-based” type had a significantly higher food security score than the two other types than had similar level, while the “Crop-based” households performed significantly better in health and wellbeing than the “Crop-livestock-based” and significantly more than the “Multi-activity-based” type. Household types did not display any significant difference in terms of social capital and land security, for the latter variable due to the high variability of value in the “Crop-livestock based” type.

### 3.3. Determinants of sustainability

The performance, expressed as index for the three sustainability pillars, showed relations in some cases to different farm characteristics depending on the region (Table 4). Despite the general low adjusted R-squared values, the models provide general influence of household variables over the sustainability indices. The low regression coefficients in Table 4 can be explained by the fact that the response variable varies between 0 and 1. According to model results, an increase of household size by one member in Dodoma, will decrease the economic sustainability by 0.008 (Table 4). A few relationships were common to both regions, such as the proportion of produce sold and the economic sustainability pillar (Table 4).

In both regions, the market orientation of farms, measured as share of crop production sold, was significantly positively correlated with economic sustainability (Table 4). The sale of crop products represented an incentive that may result in better performance in crop production; a

**Table 3**
Summary statistics of composite sustainability indices for the household types of environmental, economic and social sustainability. The mean score is presented with the standard deviation in parenthesis for each type in each region. Comparisons among the types are done separately for each region.

| | | Dodoma | | | | | Morogoro | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Household type | | All | Gathering-based | Crop-based | Livestock-based | Self-employment-based | All | Multi-activity-based | Crop-based | Crop-livestock-based |
| | Number of households | 448 | 114 | 221 | 88 | 25 | 443 | 165 | 262 | 16 |
| Environ- | Soil | 0.37 (0.13) | 0.34 (0.12)$^{a}$ | 0.37 (0.14)$^{a}$ | 0.43 (0.13)$^{b}$ | 0.39 (0.14)$^{ab}$ | 0.30 (0.10) | 0.28 (0.11)$^{a}$ | 0.30 (0.09)$^{a}$ | 0.29 (0.08)$^{a}$ |
| -ment | Water | 0.74 (0.12) | 0.73 (0.11)$^{ab}$ | 0.77 (0.12)$^{b}$ | 0.70 (0.12)$^{a}$ | 0.70 (0.11)$^{a}$ | 0.80 (0.09) | 0.79 (0.10)$^{a}$ | 0.81 (0.09)$^{b}$ | 0.78 (0.10)$^{ab}$ |
| | Diversity | 0.23 (0.12) | 0.18 (0.10)$^{a}$ | 0.22 (0.12)$^{b}$ | 0.33 (0.14)$^{c}$ | 0.34 (0.15)$^{c}$ | 0.19 (0.12) | 0.18 (0.12)$^{a}$ | 0.19 (0.12)$^{a}$ | 0.18 (0.13)$^{a}$ |
| Economy | Crop performance | 0.53 (0.08) | 0.50 (0.06)$^{a}$ | 0.56 (0.09)$^{b}$ | 0.51 (0.09)$^{a}$ | 0.53 (0.13)$^{ab}$ | 0.6 (0.13) | 0.53 (0.11)$^{a}$ | 0.66 (0.14)$^{b}$ | 0.49 (0.16)$^{a}$ |
| | Profitability | 0.21 (0.18) | 0.09 (0.09)$^{a}$ | 0.19 (0.18)$^{b}$ | 0.43 (0.31)$^{c}$ | 0.42 (0.37)$^{c}$ | 0.30 (0.29) | 0.23 (0.29)$^{a}$ | 0.32 (0.28)$^{b}$ | 0.47 (0.42)$^{b}$ |
| | Stability | 0.27 (0.25) | 0.24 (0.22)$^{a}$ | 0.27 (0.26)$^{a}$ | 0.29 (0.25)$^{a}$ | 0.32 (0.28)$^{a}$ | 0.46 (0.28) | 0.40 (0.27)$^{a}$ | 0.50 (0.28)$^{b}$ | 0.60 (0.25)$^{b}$ |
| | Vulnerability | 0.64 (0.24) | 0.64 (0.24)$^{a}$ | 0.64 (0.24)$^{a}$ | 0.64 (0.23)$^{a}$ | 0.59 (0.23)$^{a}$ | 0.81 (0.22) | 0.81 (0.22)$^{b}$ | 0.84 (0.21)$^{b}$ | 0.66 (0.32)$^{a}$ |
| Social | Food security | 0.43 (0.16) | 0.37 (0.18)$^{a}$ | 0.44 (0.15)$^{b}$ | 0.50 (0.15)$^{c}$ | 0.59 (0.18)$^{c}$ | 0.57 (0.18) | 0.56 (0.17)$^{a}$ | 0.57 (0.18)$^{a}$ | 0.77 (0.20)$^{b}$ |
| | Health | 0.66 (0.21) | 0.66 (0.22)$^{a}$ | 0.65 (0.21)$^{a}$ | 0.67 (0.20)$^{a}$ | 0.65 (0.21)$^{a}$ | 0.63 (0.20) | 0.59 (0.24)$^{a}$ | 0.66 (0.17)$^{b}$ | 0.57 (0.20)$^{ab}$ |
| | Wellbeing | 0.62 (0.23) | 0.65 (0.21)$^{a}$ | 0.63 (0.23)$^{a}$ | 0.58 (0.27)$^{a}$ | 0.57 (0.28)$^{a}$ | 0.76 (0.20) | 0.73 (0.21)$^{a}$ | 0.80 (0.19)$^{b}$ | 0.77 (0.18)$^{ab}$ |
| | Social capital | 0.23 (0.23) | 0.23 (0.24)$^{a}$ | 0.22 (0.23)$^{a}$ | 0.26 (0.22)$^{a}$ | 0.46 (0.31)$^{b}$ | 0.22 (0.20) | 0.21 (0.20)$^{a}$ | 0.20 (0.19)$^{a}$ | 0.29 (0.17)$^{a}$ |
| | Land security | 0.49 (0.18) | 0.47 (0.18)$^{a}$ | 0.49 (0.17)$^{a}$ | 0.52 (0.19)$^{a}$ | 0.52 (0.21)$^{a}$ | 0.44 (0.17) | 0.43 (0.15)$^{a}$ | 0.44 (0.18)$^{a}$ | 0.37 (0.25)$^{a}$ |
| | Environmental index | 0.45 (0.07) | 0.41 (0.06)$^{a}$ | 0.45 (0.08)$^{b}$ | 0.49 (0.08)$^{c}$ | 0.48 (0.08)$^{bc}$ | 0.43 (0.06) | 0.42 (0.07)$^{a}$ | 0.43 (0.06)$^{b}$ | 0.42 (0.06)$^{ab}$ |
| | Economic index | 0.42 (0.10) | 0.37 (0.09)$^{a}$ | 0.42 (0.11)$^{b}$ | 0.47 (0.11)$^{c}$ | 0.46 (0.14)$^{bc}$ | 0.54 (0.13) | 0.50 (0.12)$^{a}$ | 0.58 (0.14)$^{b}$ | 0.56 (0.19)$^{ab}$ |
| | Social index | 0.49 (0.10) | 0.48 (0.10)$^{a}$ | 0.49 (0.10)$^{a}$ | 0.51 (0.10)$^{ab}$ | 0.56 (0.11)$^{b}$ | 0.52 (0.09) | 0.50 (0.09)$^{a}$ | 0.53 (0.08)$^{b}$ | 0.55 (0.08)$^{ab}$ |
| | Overall index | 0.45 (0.06) | 0.42 (0.06)$^{a}$ | 0.45 (0.06)$^{b}$ | 0.49 (0.07)$^{c}$ | 0.50 (0.07)$^{c}$ | 0.50 (0.07) | 0.47 (0.07)$^{a}$ | 0.51 (0.07)$^{b}$ | 0.51 (0.09)$^{ab}$ |

The letters show significant differences among the types within each region with $p < 0.05$, as Dodoma and Morogoro are threated independently. Combination of letters show a significant difference only with $p < 0.10$.

**Table 4**
Results of linear regression models applied to explain the contribution of farm household characteristics to economic, environmental and social sustainability indices for Dodoma and Morogoro. Only explanatory variables showing significant correlations ($P \leq 0.01$) are shown.

| | Economic sustainability | | Environmental sustainability | | Social sustainability | |
|---|---|---|---|---|---|---|
| Explanatory variables | Dodoma | Morogoro | Dodoma | Morogoro | Dodoma | Morogoro |
| Intercept | $4.4e^{-01}$*** | $3.0e^{-01}$*** | $3.5e^{-01}$*** | $3.8e^{-01}$*** | $5.1e^{-01}$*** | $4.7e^{-01}$*** |
| Household size | $-8.6e^{-03}$*** | $2.5e^{-03}$ | $4.2e^{-03}$** | $3.4e^{-03}$* | $-4.5e^{-03}$* | $-7.2e^{-04}$ |
| Age of household head | $-5.3e^{-04}$ | $-4.7e^{-04}$ | $3.7e^{-04}$ | $-2.5e^{-04}$ | $-7.5e^{-04}$* | $-7.0e^{-04}$** |
| Labour investment | $-1.2e^{-05}$ | $2.8e^{-06}$ | $-2.3e^{-06}$ | $1.1e^{-05}$** | – | – |
| Hired labour (%) | $-7.9e^{-02}$* | $-7.1e^{-02}$* | $-3.54e^{-03}$ | $-8.8e^{-03}$ | $1.1e^{-01}$** | $3.8e^{-02}$* |
| Land size | $-6.4e^{-04}$ | $1.4e^{-03}$ | $4.6e^{-03}$** | $6.8e^{-03}$*** | $2.7e^{-03}$ | $-8.4e^{-04}$ |
| Size of cattle herd | $1.2e^{-03}$ | $6.2e^{-03}$ | $1.9e^{-02}$*** | $-6.0e^{-03}$ | $5.6e^{-03}$ | $6.4e^{-03}$ |
| Size of poultry flock | $-9.5e^{-03}$ | $1.1e^{-01}$** | $9.1e^{-02}$* | $1.0e^{-01}$*** | $1.1e^{-02}$ | $5.3e^{-02}$* |
| Size of pig herd | $1.6e^{-02}$ | $8.8e^{-02}$ | $1.2e^{-02}$ | $6.7e^{-02}$** | $1.3e^{-02}$ | $-2.0e^{-02}$ |
| Crop income (%) | $2.5e^{-02}$ | $1.6e^{-01}$*** | $4.9e^{-02}$ | $7.7e^{-03}$ | $5.2e^{-02}$ | $6.5e^{-02}$* |
| Self-employment income (%) | $3.5e^{-02}$ | $1.9e^{-01}$*** | $2.4e^{-02}$ | $2.5e^{-02}$ | $1.8e^{-02}$ | $-1.0e^{-02}$ |
| Crop production sold (%) | $1.3e^{-01}$*** | $2.0e^{-01}$*** | $6.9e^{-02}$*** | $3.8e^{-02}$** | $3.6e^{-02}$ | $1.0e^{-02}$ |
| Food expenditure | $1.2e^{-05}$ | $6.9e^{-06}$ | $7.0e^{-06}$ | $-7.1e^{-06}$* | $6.7e^{-06}$ | $2.0e^{-05}$*** |
| Adjusted R-squared | 0.21 | 0.29 | 0.25 | 0.20 | 0.11 | 0.13 |

significant positive correlation between share of production sold and crop performance index supported this relationship. On the other hand, in both regions, hiring labour for crop activities was negatively correlated with economic sustainability (Table 4). The high cost of labour relative to additional benefits gained may have resulted in it being economically unviable. In Dodoma, size of household was significantly negatively correlated with economic sustainability (Table 4). Regression results showed that households in Dodoma with more family members tended to be less economically stable and more vulnerable to shocks. More specifically, cattle owners showed lower vulnerability to shocks. In Morogoro, proportion of income from crops, self-employment and livestock was significantly positively correlated ($P \leq 0.05$) with economic sustainability (Table 4), and all these were correlated with higher profitability. This suggests that committing to one of these livelihood strategies can lead to increased economic sustainability for households in the region.

Market orientation was also significantly positively correlated with environmental sustainability in both regions, along with size of managed area, household and poultry flock (Table 4). Market orientation showed positive correlations with soil and diversity scores in Dodoma, and with water and diversity scores in Morogoro. Size of holding was positively correlated with agricultural diversity, with larger land area allowing more species to be grown. Larger households tended to show more efficient use of water resources in Morogoro and a higher agrobiodiversity in Dodoma. Poultry was common in both regions and contributed to agrobiodiversity. In Morogoro, poultry was a potential source of animal manure for crop fields. In Dodoma, size of small-ruminant herd was significantly positively correlated with environmental sustainability. In Morogoro, size of pig herd was positively correlated with environmental sustainability (Table 4). Livestock rearing significantly contributed to agrobiodiversity in both regions and to manure production. Food expenditure showed a significant negative correlation with environmental sustainability in Morogoro (Table 4). Households with more valuable assets tended to have less diverse farming systems. Food expenditure was also negatively correlated with water management, due to higher food expenses in households with irrigation systems.

For social sustainability, we found a significant positive relationship between food expenditures and social sustainability in Morogoro (Table 4). This could particularly be linked to the food security component as food expenditures allow to buy more diverse food at household level. The age of household head was negatively correlated to social sustainability. Hired labour was significantly positively correlated with social sustainability in both regions. This could be due to the fact households with the means to hire labour can reinvest the benefits from hired labour into better living conditions. Size of household was significantly negatively correlated with social sustainability in Dodoma as found for economic sustainability (Table 4). Food-insecure households tended to be larger and have an older household head. Size of poultry flock, share of income from crops and food expenditure were positively correlated with social sustainability in Morogoro (Table 4).

## 4. Discussion

### *4.1. Relationships between sustainability pillars across regions and farm household types*

This study showed that economic development does not always preclude environmental conservation. In fact, economic sustainability was significantly positively correlated with environmental and social sustainability in both study regions. Thus the relationship between natural and financial capital can be mutually reinforcing. Declining crop yields were found to be positively correlated with declining soil fertility, which implies that lower environmental sustainability leads to lower economic sustainability. Consequently, households may reinvest economic gains in soil fertility, e.g. through application of fertiliser. Households lacking the means to invest in soil fertility are likely to become locked in a vicious circle, explaining why low-endowment farms typically display low soil fertility rates (Tittonell et al., 2010). However, concerning the relationship between economic sustainability and sustainable management of natural resources, an exception was found for water management, with better economically performing households consuming water more intensively, e.g. for irrigation.

Crop and livestock diversity allowed maintenance of a broader range of biological resources and supported economic sustainability, with household types with livestock displaying better stability than other households. In fact, agricultural diversity was positively correlated with economic sustainability in both regions. Integration of livestock into the farming system, which increased biological diversity in our indicators, appeared to lower the economic vulnerability of smallholder farms. Tittonell, (2014b) found that owning livestock enables smallholders to accumulate capital that can be used to absorb shocks and unexpected needs, and concluded that non-livestock farms, which are unable to stock and de-stock in this way, are often stuck in a poverty trap.

Among households with similar asset levels, those with crop-based livelihoods performed better than those with off-farm income (“Gathering-based” in Dodoma and “Multi-activity-based” in Morogoro). By using natural, physical and financial resources, livelihood strategies can have a significant impact on sustainability levels in all three pillars. Households with similar levels of assets had made different choices of livelihood, which had implications for sustainability. A possible reason for this is landholding fragmentation, as “Gathering-based” households had on average twice the proportion of remote crop fields (more than 30 min away from the homestead) than “Crop-based” households, and were 25–40% smaller in area. This difficulty in accessing land for crop production could lead households to invest their time in other activities, e.g. firewood and wild food collecting. This livelihood diversification strategy, where farm households look for off-farm income sources in addition to agricultural income, is often used as a coping mechanism by the most disadvantaged households with fragmented land (Scoones, 1998). Although livelihood diversification can help cope with shocks and lower risks, e.g. due to market failures, it can also impede improvement of the farming system by diverting labour and other resources away from the farm. In a study conducted in Kenya and Uganda, Tittonell et al. (2010) found that farms with small land-to-labour ratio and high off-farm income reliance had lower rates of food self-sufficiency. These off-farm income activities brought a low level of income, threatening food security for farm households suffering from overall low profitability and with insufficient funds for necessary food expenses. Moreover, gathering activities conducted by “Gathering-based” or “Multi-activity-based” households could pose a threat to environmental sustainability outside household borders, since e.g. fuelwood and wild food collection exert substantial pressure on protected and non-protected natural areas (Brashares et al., 2011; Laurance et al., 2012; UNEP, 2010). Ultimately, these activities can provoke a tragedy of the commons, a situation first described by Hardin (1968) where individual users cause depletion of shared natural resources through their collective action. A report published by the International Institute of Environment and Development (IIED) describes a tragedy of the commons in Tanzania, where granting access only (and not management rights) often results in serious degradation of state-owned forests due to overexploitation by villagers (Wily, 2001). In some cases, livelihood diversification through self-employment activities like cooking, petty trading or local brewing, as performed by the households with higher capital in Dodoma, can be an active choice to accumulate capital and reinvest it in agriculture or other activities (Scoones, 1998). These households depend heavily on self-employment and have younger and more educated heads, which can be an advantage in accessing off-farm work and potentially “stepping out” of agriculture (Wilkus et al., 2019), or in investing in more productive, market-oriented farming using improved agricultural techniques.

Based on household assets and level of sustainability in farming systems, we formulated some suggestions on livelihood strategy changes and sustainable intensification to improve the sustainability of farming systems type as recommended in the literature (Mahon et al., 2017). The “Self-employment-based” in Morogoro have the opportunity to “step out” of agriculture as a strategy to escape poverty (Fig. 4). Those households have accumulated capital that they can invest in different activities, providing better income perspectives (Dorward et al., 2009). On the other hand, the gathering based households are at risk of being in a poverty trap (Fig. 4), where their constraints are such that they cannot change trajectory to “step up” by improving agricultural production or “step out”, therefore staying in the same unsustainable pattern (see Tittonell, (2014b) and Tittonell and Giller, (2013) for an in-depth conceptualisation of the poverty trap). Particularly, we observed that the size of the household could further impede the stepping-up from the

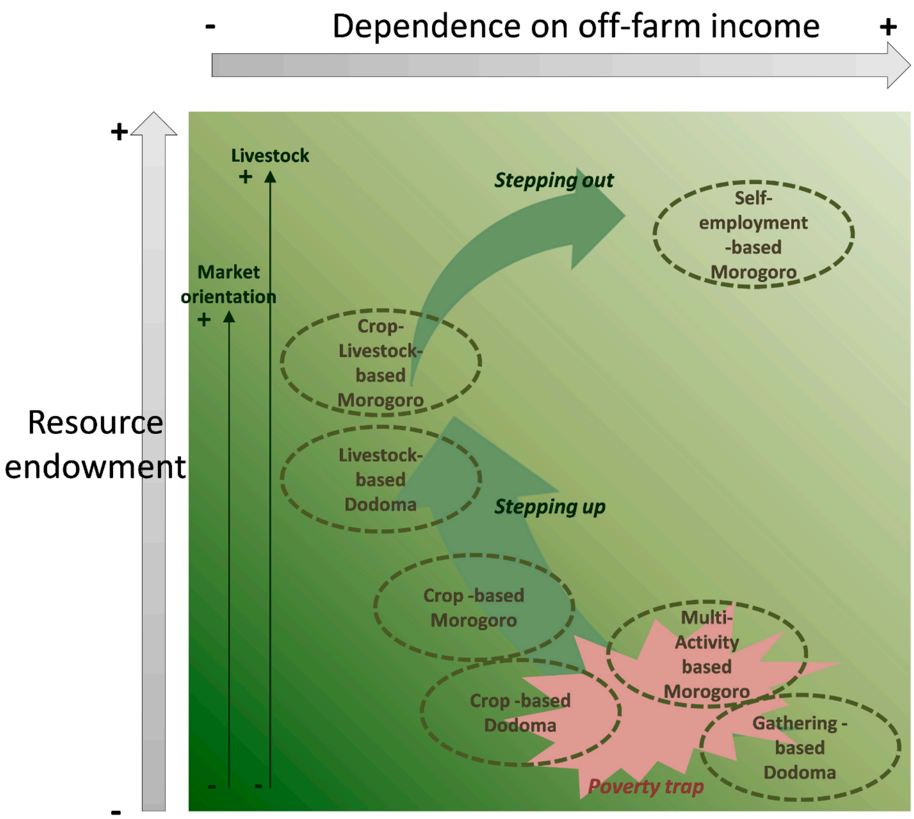


**Fig. 4.** Potential pathways of change for farm households in Dodoma and Morogoro. The poverty-trap represents the current status of three household types for which the outcomes of activities are not sufficient to invest in production to reach higher level of food security. "Crop-livestock-based" households in Morogoro and "Livestock-based" households in Dodoma managed to step-up in terms of sustainability with livestock and use of fertilisers while the "Self-employment-based" type in Morogoro stepped-out of agriculture to achieve higher level of sustainability. Representation inspired by the multidimensional approach to household typology presented in Tittonell et al. (2010).

poverty trap as larger household size have reduced economic sustainability as found in Tanzania previously (Mutabazi et al., 2015). This could be explained by a insufficiently performing farming system where the outcomes are not high enough for sustaining a larger family and additional family manpower leads to more needs but insufficient work to fulfil those needs. However, such observations could be biased by the fact that we did not collect disaggregated age data of individual household members and our analysis does not capture the non-linear relationship between household size and poverty.

The limitations on those households need to be lifted by social security programmes before they can adopt technologies improving agricultural productivity (Tittonell et al., 2010). In both regions, market orientation of production and livestock were major drivers of trajectories leading to improved household sustainability (Fig. 4).

### 4.2. Recommendations for sustainable intensification

Our analysis validates our hypothesis as households that have the lowest level of capital, here "Gathering-based" households in Morogoro and "Crop-Based" households in Dodoma are indeed the least sustainable. Their lack of initial assets calls for different strategies and practices to allow them to step-up in terms of sustainability.

Based on the sustainability of the farming system and the capitals of household, good agronomic practices with potential for contributing to sustainable intensification across these two regions of Tanzania and similar contexts can be made (Kuyah et al., 2021). Such practices have been shown to have positive outcomes in terms of income, productivity and subsequently food security in Tanzania in overall (Kim et al., 2019) but we here discuss their potential accounting for household types. "Livestock-based" and "Crop-livestock-based" types can invest the necessary natural, financial and human resources for intensification. According to Wilkus et al. (2019), the households best suited for sustainable agricultural intensification have higher income, are market-oriented and have extensive social networks. However, households who rely most on crop income ("Crop-based" households in Dodoma and Morogoro) are likely to see great improvements from implementation of low capital investment options for sustainable intensification, including intercropping, optimised weeding, use of fertilisers, rainwater harvesting and better livestock integration. The success of such options is dependent on i) farm household type, ii) regional biophysical context, including soil fertility and rainfall level, and iii) the broader socio-ecological context, including policy, advisory and social relationships that can increase ease of access and implementation of options.

Intercropping and optimised weeding are two major options for sustainable intensification in households with limited holding size but accessible workforce (e.g. "Gathering-based" households), to increase their agrobiodiversity and potentially access markets through selling surplus produces. Intercropping cereals (or cash crops such as sesame and sunflower) with legumes can boost the production of crops per unit land for home consumption and fodder, with land equivalent ratio (LER) of about 1.5 based on other regions in Tanzania (Kuyah et al., 2021; Nassary et al., 2020). Moreover, intercropping helps controlling weeds and regulating pest and disease populations (Franke et al., 2018; Rusinamhodzi et al., 2012). Legumes also have an important role in increasing food security of households (Kiwia et al., 2019). More complex technology such as doubled-up legume technology with intercropping of two legumes with one cereal could also be promoted as none of the household surveyed in this study had adopted such technology (Smith et al., 2016). Optimised weeding, which targets soil water conservation and suppression of parasitic weeds through better timing, would be an appropriate technique to achieve better use of household labour and hired labour in improving productivity (Teka, 2014). "Gathering-based" households would be able to implement this strategy since it requires low financial and natural investment (adapted to small land areas), which is a constraint to adoption in Tanzania (Jambo et al., 2019), but they would have to invest more time and labour in crop production. This is likely, because labour for own crop production is more profitable than off-farm activities such as agricultural wage labouring, which is often performed outside the village and thus has lower economic efficiency per hour invested.

Fertiliser application per unit land and use of better cultivars can be powerful drivers of soil fertility and productivity, however the adoption of these practices are low for “Gather-based” and “Multi-activity-based” households based in Dodoma and Morogoro, respectively. In *meta*-analysis with 165 paired yield outcomes across SSA, Tonitto and Ricker-Gilbert (2016) reported that micro-dosing improved grain yields by 47%. Fertiliser application has been a successful strategy in the Mbeya region in southern Tanzania, which has similar biophysical characteristics to Morogoro (Komarek et al., 2018). In the Abuja Declaration, the African Union set a target of average fertiliser use of 50 kg/ha. Tanzania has policies aiming to reduce the cost of fertilisers to approach this goal (Cameron et al., 2017). Combined with intercropping, the use of fertiliser can also enhance the overall benefits provided by intercropping and prevent nutrient mining in soils (Kiwia et al., 2019; Mugi-Ngenga et al., 2021). “Crop-based” households in Morogoro could benefit from such an intervention leading to improved soil fertility and higher yields, leading to an overall boost of the profitability. However, good efficiency of fertiliser application also requires farmer training and knowledge of the right dose and time of application, and depends strongly on soil water availability (Schindler et al., 2016).

To improve soil water availability, we recommend implementation of rainwater harvesting, which is a cost-effective strategy for coping with droughts in a rainfall-limited context (Mak-Mensah et al., 2021). However, the literature on the effect of rainwater harvesting shows diversified impacts. As regards policy, farmers’ assessment of positive yield, income, market participation and food diversity outcomes deriving from implementation of rainwater harvesting techniques show significantly different levels of anticipated improvement between the two regions (Schindler et al., 2016). Coupling rainwater harvesting with fertiliser use in Dodoma would increase the productivity and food security of “Gathering-based“ households, which had the lowest crop performance, and of “Crop-based” households.

Better integration of livestock into the farming system has substantial potential to improve the sustainability of smallholders, by increasing living capital, soil fertility and food security (Herrero et al., 2010). In Dodoma, “Gathering-based” and “Crop-based” household could improve their productivity by increasing their cattle herd and the associated number of ploughs as advised in other context like in India to a certain level (Chand et al., 2015) which needs to be local determined. However, these households are often limited by the size of their landholding and need grazing areas outside the farm. Availability of communal grassland with an effective management system in the village is a necessary condition for livestock increases and avoidance of a tragedy of the commons, such as that mentioned earlier for forests in Tanzania. In Morogoro, adoption and good management of poultry flocks seems to be a well-suited livestock option to improve sustainability across dimensions. For households with larger herds/flocks (“Livestock-based” and “Self-employment-based” types in Dodoma), fodder production and access to veterinary care can enhance livestock productivity. “Livestock-based” households could also benefit from training on manure use, in order to improve soil fertility and yields, as suggested for livestock farmers with similar characteristics in Mali (Falconnier et al., 2017). Such integration would require a localised expertise able to technically inform farmers over the type and management of animals (Ndah et al., 2020).

Implementation of strategies relying on external inputs (e.g. fertilisers, improved seeds) and accumulation of capital (e.g. livestock) needs to be supported by credits targeting those specific needs. Social capital is another sustainability component that would benefit from policy support. Farmers’ groups play a key role in accessing markets, which proved to be an important driver of sustainability in the present study. The best-performing households had the strongest social capital, manifesting itself mostly as an information network in Dodoma and farmers’ group participation in Morogoro. In a study analysing adoption of sustainable agricultural practices by smallholders in rural Tanzania, Kassie et al., (2013) found that social capital, advisory services and land tenure status influenced farmers’ investment in those practices. Thus, they concluded that policies aimed at organising farmers into cooperatives, improving land security and enhancing the skills of advisors can increase adoption of sustainable practices. Moreover, cooperative management schemes can increase human capacity, storage, bulking and transportation, while ICT support services can increase access to market information (Wilkus et al., 2019), making such policies essential for sustainable intensification.

### 4.3. *Impact of the combined assessment method on results and limitations of the study*

Sustainability assessment is a subjective process that depends on choices made on e.g. the type of challenges at stake and associated indicators, weighting and aggregation of indicators (Binder et al., 2010). Some sustainability themes were outside the scope of this study, e.g. pesticides were not considered in environmental sustainability scores because households reported marginal use in the study areas. The complex issue of erosion was covered by very simple indicators, such as tree density and area under erosion control methods, and would require biophysical measurements for more precision. Long-term monitoring of farms should be undertaken to approach impact indicators such as loss of soil for erosion rather than pressure indicators, in this case tree density, which may not always be significantly correlated to the endpoint impact (Chopin et al., 2021). The greenhouse gas emissions component of sustainability was not assessed, assuming that households had a very low carbon footprint far below unacceptable levels (Ntinyari and Gweyi-Onyango, 2021). In terms of indicators, we chose to integrate crop diversity at farm level as a direct component of sustainability, as often done in farm assessment (e.g. Paracchini et al., 2015) considering its direct influence on sustainability of farms in various contexts. Despite not using any participatory process and being constrained by available information, our selection of indicators was very similar to that achieved in a Delphi process related to a farming system assessment in Tanzania (Munyaneza et al., 2019), although excluding milk-specific indicators which are not relevant in our study areas. When using composite indices to assess sustainability, it is debatable whether the method of weighting can change observed sustainability outcomes, with both positivist and subjective approaches existing to determine weights. However, Gómez-Limón and Sanchez-Fernandez (2010) showed that the choice of weighting method does not make a major difference in the quantification of sustainability. The method of aggregation plays a more important role, with the differences being due to the degree of compensation allowed between indicators, i.e. whether a low value of one indicator can be compensated for by a high value of another. In our case, compensation was allowed among indicators, but the effect on the results was limited by evaluating all components independently.

Our models linking the three sustainability pillars and farm household structure and strategies explained a limited proportion of the variability in sustainability, as indicated by low R-squared values. This can be due to the aggregation process, which introduces more subjectivity into the assessment, thus reducing the explanatory power of the analysis. It also means that factors external to the household have a strong influence on its sustainability, i.e. fluctuations in agricultural price or climate. For instance, Nwaiwu et al., 2013 found a negative relationship between climate change and agricultural sustainability in Nigeria based on a model that included both farm characteristics and a climate change index. In our study, households that reported being affected by droughts over the past five years tended to perform less well economically, as shown by a significant negative correlation between economic sustainability and reports of droughts. Thus, climate factors relating to water availability in particular have a considerable impact on sustainability in the context of sub-Saharan Africa.

 

## 5. Conclusions

A novel method combining the sustainable livelihood approach with farm sustainability assessment revealed sustainability strengths and weaknesses of different types of farm households in rural Tanzania. These were associated with livelihood strategies in different contexts and their identification enabled formulation of recommendations tailored to the regional context and household type. Based on the results, we recommend promoting adoption of intercropping techniques for "Gathering-based" and "Multi-activity-based" farm household types, as they can increase production/productivity on their limited land area and with their available workforce. Integration of livestock with crop production should be promoted for "Crop-based" farm household types, to increase soil fertility (with manure) and enhance food security with direct consumption of animal products or income from livestock, especially in the event of climate or price shocks. In Dodoma, increased rainwater harvesting, livestock integration with crops and fertiliser use and application rates would help cope with limited available water and reverse the decrease in soil fertility. To facilitate adoption of these sustainable intensification options, agricultural policies and food security programmes need to be locally tailored and implemented with appropriate training and consultation on management of common resources used for livestock.

### CRediT authorship contribution statement

**Defne Ulukan:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Göran Bergkvist:** Writing – review & editing. **Marcos Lana:** Writing – review & editing. **Anja Fasse:** Writing – review & editing. **Gregor Mager:** Writing – review & editing. **Ingrid Öborn:** Writing – review & editing. **Pierre Chopin:** Conceptualization, Methodology, 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

the data is provided in zip file with the paper

### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109518.

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