Agricultural Systems 203 (2022) 103496

Contents lists available at ScienceDirect

Agricultural Systems

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

Contributions of integrated soil fertility management (ISFM) to various sustainable intensification impact domains in Tanzania

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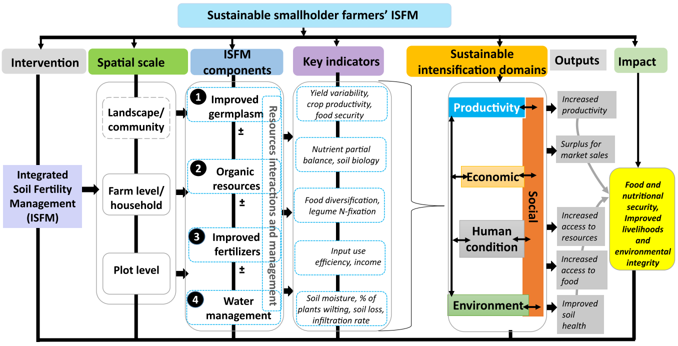
HIGHLIGHTS

- The contributions of ISFM to domains of sustainable intensification are presented.
- Number and combinations of ISFM components used by farmers vary widely even in one village.
- Intercropping, improved seeds and manure are more commonly used in sub-humid relative to semi-arid zone.
- Productivity and economic benefits are affected by number and specific components of ISFM used.
- Differential access to resources and decision making influence ISFM components used.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Mark van Wijk

Keywords:
ISFM components
Impact domains

ABSTRACT

CONTEXT: The implementation of integrated soil fertility management (ISFM) varies widely among farmers, from no ISFM to multiple computations of ISFM components (i.e., improved germplasm, organic resources, fertilizers, and local adaptations e.g., soil and water conservation (SWC)). There is no comprehensive report on farmers' use of ISFM components and their impact on sustainable intensification domains of productivity, economic, social, human condition, and environment and the associated variations across farmer fields and agro-ecological zones (AEZs).

OBJECTIVE: This study 1) evaluated the current implementation status of ISFM by farmers in relation to the various ISFM components and 2) provided multi-dimensional multi-scale evidence of ISFM implications that can guide ISFM investments within SSA contexts, with a specific focus on Tanzania.

METHODS: We used data collected from 1406 plots between 2013 and 2020 in semi-arid and sub-humid AEZs. The data are from farmer practices. The plots were grouped by the various combinations of ISFM components

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https://doi.org/10.1016/j.agsy.2022.103496
Received 14 February 2022; Received in revised form 26 August 2022; Accepted 1 September 2022

implemented and analysed using Tukey's test to examine the association of ISFM use with selected indicators within a domain.

RESULTS AND CONCLUSIONS: The number of ISFM components used by farmers is higher in sub-humid (1 to 4) than in semi-arid AEZ (0 to 3). Except for SWC used by 40% of farmers in both AEZs, the proportion of farmers using improved seeds (95%) and manure (55%) in the sub-humid AEZ are more than double those using these ISFM components in the semi-arid AEZ. Productivity and economic benefits increase with the number of ISFM components at the expense of higher labour demand. Increasing plot-level ISFM benefits also translate to increased household-level whole-farm income but contributions to human nutrition are unclear. The contribution to SOC by increasing ISFM is insignificant, compounded by strong effects of slope position of the field. Differential access to resources, decision-making and control rights drive the number and choice of the specific ISFM components.

SIGNIFICANCE: Understanding of ISFM impacts across domains is essential to guide the scaling of ISFM in Tanzania and beyond and therefore recommended in future studies.

1. Introduction

Global challenges of increased food demand amidst climate change present the need for sustainable farming practices to be employed widely by farmers (Garnett et al., 2013; Springmann et al., 2018). Many farming practices such as fertilizer use, agroforestry, and conservation agriculture are being promoted in sub-Saharan Africa (SSA) and elsewhere to increase yields, income, food security and reduce poverty (Amadu et al., 2020; Hörner and Wollni, 2021; Khonje et al., 2018). Unfortunately, these are rarely assessed simultaneously across multiple dimensions of sustainability, especially the effects on the environment and human condition aspects such as nutrition, food security, and health. On top of that, concerns around farming practices and equity issues do need stronger attention if adoption is to equally benefit women and men and other socially differentiated groups. Women's lower control over agricultural land for instance may constitute a constraint to long-term soil investments such as through soil and water conservation (SWC) practices (Zhang et al., 2021).

In the last few years, a sustainable intensification assessment framework (SIAF) was designed to guide the assessment of practices proposed for sustainable intensification through multiple indicators in each of the productivity, economics, environment, social and human condition domains (Musumba et al., 2017). This is a relatively recent framework with only a few applications, for example, in Malawi assessing crop management practices (Snapp et al., 2018) and Ghana on the sustainable production of groundnuts (Abdul Rahman et al., 2020). None of the studies specifically evaluated integrated soil fertility management (ISFM) across the domains and considered multiple farms.

ISFM involves combinations of nutrients from organic and inorganic sources alongside improved germplasm, while addressing local constraints such as soil water availability and acidity/alkalinity that impede expected nutrient use efficiencies (Vanlauwe et al., 2010). While farmers should ideally implement several of these components of ISFM in their farming practices simultaneously, this is often hardly the case. This relates to the specific needs due to heterogeneity that exists in smallholder farming systems, 'farmers' differential capitals and assets as well as knowledge and preferences for ISFM and includes gender-specific constraints (Zhang et al., 2021). Benefits of the application of ISFM may depend on the number and specific components of ISFM in use (see Fig. 1). With this recognition, Vanlauwe et al. (2010) suggested the implementation of ISFM components as a stepwise progression building from local practices. However, the actual implementation can be highly varied among smallholder farmers, and multiple combinations of the ISFM components can be expected.

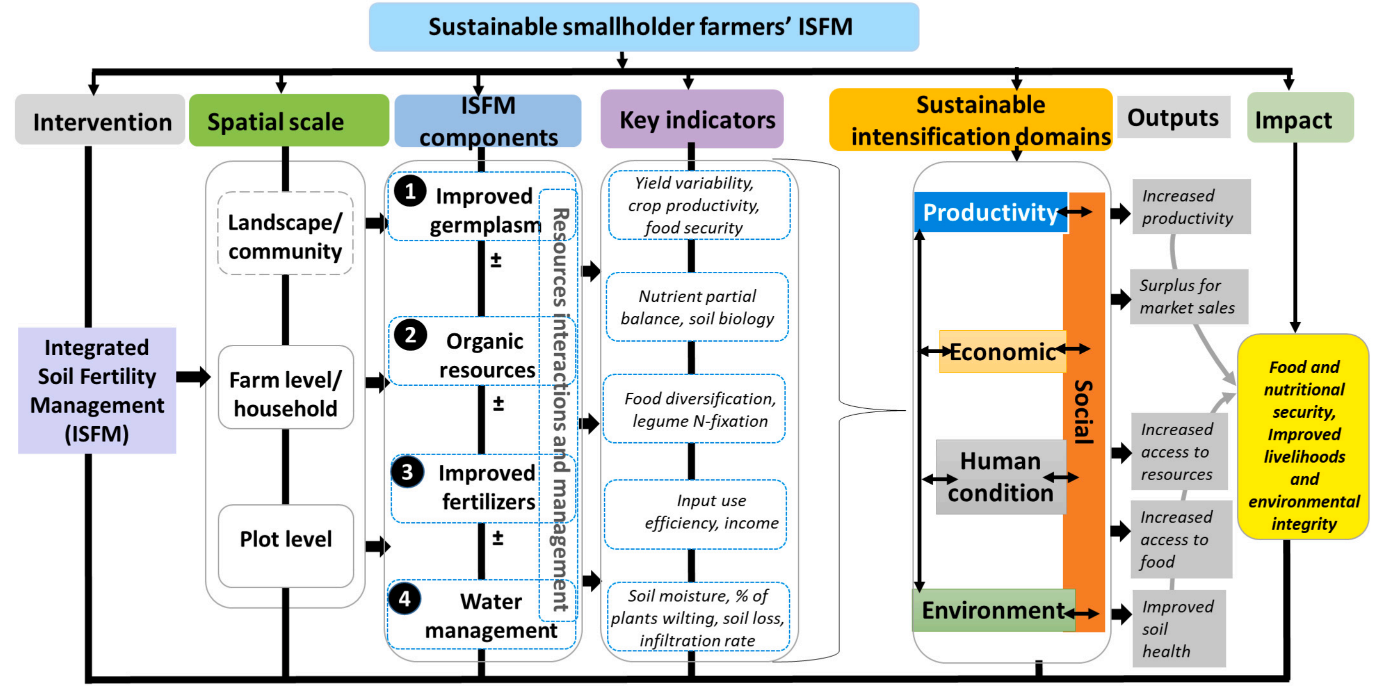

Fig. 1. The conceptual approach for multi-level assessment of integrated soil fertility management across domains of sustainable intensification as considered in this study.

Understanding the implementation status of ISFM among farmers, and the associated system benefits across multiple sustainable intensification domains is important to inform future interventions. While many studies exist on ISFM (e.g., Adolwa et al., 2019a; Hörner and Wollni, 2021, 2022), there is a lack of robust knowledge of how the extent of ISFM application by farmers influences commonly studied indicators of productivity and economics domains or the less studied environment, social and human condition domains. This study aims to fill this gap in the literature by assessing the association of ISFM adoption with indicators of the five domains.

Households practicing ISFM obtain farm/household-level benefits often not captured in most studies which operate at plot-level yet ISFM interacts with other components of the farm/household. For the household-level, it has been well established that men and women living in the same household may not pool their resources nor share their preferences for agricultural practices (Alderman et al., 1995). Therefore, gender differences in access to and control of resources for ISFM need to be considered. At the farm-level, ISFM interacts with other farm components such as livestock through feed provisioning and these are expected to influence overall benefits. The SIAF framework recognizes that implications of a practice or a technology straddle from plot to farm/household and the community/landscape levels. Applying this framework to ISFM is important to understand ISFM's benefits and tradeoffs.

Data collected over 8 years (since 2012), and covering a wide range of farmers and a diverse array of implementations of ISFM provide an opportunity for good understanding of ISFM's contributions to the sustainable intensification domains. The objective of this study was to 1) understand the current implementation status of ISFM by farmers in relation to the various ISFM components and 2) provide multi-dimensional multi-scale evidence of ISFM implications that can guide ISFM investments within SSA contexts, with a specific focus on Tanzania. We hypothesized that 1) an increasing number of ISFM components is associated with increasing benefits across many indicators of sustainable intensification domains, and 2) the use rate of ISFM components varies within and across AEZs and is strongly affected by socio-demographic factors.

2. Materials and methods

This study focused on Tanzania within SSA, a region characterized by high yield gaps, increasing climate variability, food and nutritional gaps, high levels of nutrient mining, and increasing population growth above the growth in food production. The study locations in Tanzania were sub-humid AEZ represented by Babati district in the northern zone (Kihara et al., 2015) and the semi-arid AEZ represented by Kongwa and Kiteto districts in the central zone (Kimaro et al., 2009). The sub-humid district ranges in altitude from 1600 to 2200 m.a.s.l. The soils are mostly ferralsols with limitations of N and P and micronutrients such as Zn and Mn in specific places. Landholdings range from 1 to 2 ha in the upper altitudes (high and medium altitudes) to 3–10 ha in the low elevation areas (own data). The semi-arid districts lie between 500 and 1200 m.a.s.l, have medium-altitude plains with some hill ranges, and soils are mainly medium textured with low to moderate fertility (Mowo et al., 1993). Rainfall (average of 560 mm annually) is quite unpredictable in terms of onset and distribution over time (Mongi et al., 2010), with 48% of the rain sometimes falling toward the end of the growing season (Kimaro et al., 2009). Crop production and livestock keeping are the main economic activities in the study sites. Major food and cash crops are maize and sunflower, as well as beans (for sub-humid) and millet and groundnuts (for semi-arid), and pigeon peas (for both agro-ecologies), and their detailed data based on the baseline are contained in Charles et al. (2016).

The study approach used considers that the practice of ISFM across different farmers varies in number of components and has implications on various key indicators related to the various SIAF domains, at various spatial scales as shown in Fig. 1 above (only plot and household level are considered in this study). Four ISFM components are identified as constituting ISFM and these are:

1. Use of improved crop varieties. These are associated with better use efficiency of nutrient inputs (see Vanlauwe et al., 2011)
2. Use of organic resources. The organic component was considered when manure, crop residue retention as mulch, or incorporation was observed. Organic resources improve system performance through yields, economics, and environmental benefits (Vanlauwe et al., 2011; Kihara et al., 2020).

   A study on six crop associations either as cereal legume rotations or intercropping showed a biomass contribution ranging from 2.03 to 4.71 Mg/ha/season and a total N accumulation ranging from 87 to 180 N/ha (Gwenambira-Mwika et al., 2021). The contribution of BNF was on average 52% from pigeon pea or 66% from groundnuts. The significance of such potential contributions necessitates a specific legume focus when considering multiple domains as in our study. We underscore that, compared to cereals, legumes are often of more nutrient density hence a high contribution to nutritional outcomes within the human condition domain. Besides, legumes are often also gendered crops, i.e., influence to social dynamics within households. Therefore, under these domains, and elsewhere in this publication where relevant, the specific contributions of crop association are presented. Use of crop associations (specifically intercropping) is highly practiced in Central and Northern Tanzania (Mugi-Ngenga et al., 2021) with often high land equivalent ratios relative to monocrops (Woomer et al., 2004; Mhango et al., 2017).
3. Use of fertilizers as sources of nutrients. The amount and type of fertilizer used by farmers was not differentiated in this study as this has already been a focus of many other studies (Vanlauwe et al., 2011; Kihara et al., 2020). Instead, only use, or no use categories were considered.
4. Management of constraints to fertilizer responses, including either soil and water conservation (SWC) through ridges, terracing, rip tillage, tied ridging, contour ploughing, stone bounds, mulching, or management of soil acidity/alkalinity. These have influenced productivity, economics, and other domain indicators (Kihara et al., 2020).

Although the ISFM is implemented primarily at the plot level, it has effects even at household level such as on food security and nutrition. The metrics for measuring the effects vary depending on the assessment level. The ISFM contributes to the domains of sustainable intensification and might have tradeoff or synergy effects across the domains. For example, efficiency gains in nutrient use support environmental integrity and increase crop productivity and, consequently, economics. Of particular is the social domain, which has to be regarded as a cross-cutting domain due to its influence on all other domains, e.g., equity.

2.1. Data sources by domain

2.1.1. Productivity domain

Plot-level data on maize productivity and use of ISFM components were obtained from measurements in farmer fields and surveys conducted in different years and sites through the 2012–2020 (i.e., the survey and farmer-managed trials in Table 1). Yield measurements were from farmer practices either under farmer-managed trials or local farmer practices when conducting agronomic surveys (IITA, 2014; Kihara et al., 2015; Table 1). The agronomic survey entails focused and detailed data collection on specific crop management practices for specific plots and actual yield measurements (i.e., combining both interviews and yield measurements). The farmer-managed trials consisted of researcher-designed, farmer-managed trials all in farmer fields. They mainly involved an improved practice where fertilizers were applied, compared with the local farmer practices (data used in this study are for the local practices). Although yields were measured under the farmer practices

Table 1
Experimental and survey data used in this study, their associated spatial scales, domains and indicators under the two agro-ecological zones.

Trial objective/data collection method	Number of plots[α]	Trial type	Scale and domain	Indicators	AEZ
Farmer productivity recalls of 2012	105	Survey	Plot level [1,2]	Productivity; gross margins	Sub-humid
Situational analysis agronomic survey of 2012/13	117	Survey	Plot level [1,2,3]	Productivity; gross margins; Nutrient partial balance	Sub-humid
Testing coupon technology packages 2014	40	Farmer-managed	Plot level [1,2]	Productivity; gross margins;	Sub-humid
Farmer productivity recalls of 2016	237	Survey	Plot level [1,2]	Productivity; gross margins;	Sub-humid
Fertilizer microdosing across multiple farms in 2016	113	Farmer-managed	Plot level [1,2,5]	Productivity; gross margins;	Sub-humid
Fertilizer microdosing across multiple farms in 2017	208	Farmer-managed	Plot level [1,2,3]	Productivity; gross margins; Soil organic carbon; active carbon; Harvested proteins and Zinc,	Sub-humid
Legume and cereal variety performances (2019)	40	Researcher managed	Plot level [1]	Productivity; Nutrition (Grain N and P)	Semi-arid
Fertilizer trials in semi-arid areas (2016)	329	Farmer-managed	Plot level [1]	Productivity	Semi-arid
Household surveys of 2020	86	Survey	Plot & household [1,2,4,5]	Productivity; gross margins; labour demands; Household dietary diversity scores; Months of food insecurity; labour demand; land and income control;	Sub-humid
Household surveys of 2020	131	Survey	Plot & household [1,2, 4,5]	Productivity; gross margins; labour demands; Household dietary diversity scores; Months of food insecurity; labour demand; land and income control;	Semi-arid

[α] Except for the household surveys of 2020, the number of plots is the same as number of farmers whose fields are studied. Domains 1 = productivity, 2 = economics, 3 = environment, 4 = human condition, 5 = social.

even within the farmer-managed trials, the yields in such plots are likely higher than those in farmers' fields where there is no contact with researchers. The plots' history was obtained for all the farms to inform the other ISFM components in use. During agronomic surveys of 2013 and 2017, farmer interviews provided crop productivity data for the previous years, i.e., 2012 and 2016, referred in Table 1 as farmer productivity recalls. Household and plot -level data were obtained through farmer interviews during household surveys in 2020. Household-level data is an aggregate of data derived from multiple plots/fields managed by a farmer.

2.1.2. *Economic domain*

Economic assessments were primarily conducted using data from the plot and household survey conducted in 2020, involving 217 plots and 177 farmer fields. A plot is a portion of a farmer field under specific crop/s and managed uniformly from the rest of the plots, and a farmer field has only one or more of such plots. The farmers had been selected randomly from a large pool of ISFM farmers in semi-arid and sub-humid AEZ. A total of 131 plots and 111 farmer fields were selected in semi-arid, while 86 plots and 66 farmers' fields were selected in sub-humid AEZ. To measure the contribution of the use of ISFM to the returns to farm production, we used three indicators; (1) gross margins (US$/ha) (2) whole-farm income (US$/capita) and (3) labour (man-days/ha). Gross margin is the difference between gross revenues and the total variable costs accrued in crop production and is used to measure potential profitability. The variable costs include purchased inputs (seed, fertilizers, pesticides), labour for land operations such as land preparation, weeding, planting, and harvesting. The gross margins reported are based on all crops (main and intercrops) grown on a specific plot. Besides the 2020 plot and household survey data, other production data such as “situational analysis agronomic survey of 2013” and “fertilizer microdosing” work of 2017 were also used to calculate gross margins.

On the other hand, whole farm income includes all income from crops and livestock less all the associated variable and fixed costs (Mutenje et al., 2019; Torkamani, 2005). Because it combines crops and livestock, we use whole farm income per capita, i.e., whole farm income divided by the household size. Lastly, we estimated the labour associated with using the different components of ISFM. Labour was calculated in man-days/ha (a one man-day is equivalent to 8 h of work per day).

Costs and prices used in the economic assessments were specific for each site and year. The analysis included all the crops grown by a farmer.

2.1.3. *Environment domain*

Soil organic carbon (SOC) and active carbon were measured for the top soils (0–15 cm depth) of the 208 farmers' practice plots in the fertilizer microdosing survey of 2017. The soil samples were obtained from 4 points within a plot using a Y-shaped pattern, i.e., one auger hole in the middle and 3 at the ends of the Y. The soils from the four auger holes were thoroughly mixed and a composite sample taken for laboratory analysis. The soil measurements were undertaken at CIAT laboratories in Nairobi using a CN elementar analyser for SOC and a mobile SoilDoc test kit for the active carbon (Weil et al., 2003).

Regarding management in all the plots used under the environment domain, land preparation was by animal/tractor ploughing while weeding was by hand-hoes as commonly done in the area. Also, all plots were planted with improved maize varieties mostly (98% of plots) including pigeonpea intercrop. Manure application and slope position characterizing each plot were captured as part of the agronomic survey.

2.1.4. *Human condition domain*

Here, indicators address nutrition (household dietary diversity [HDD] and nutritional requirement) and food security (months of food insecurity).

To assess the association between the use of ISFM and HDD, we constructed HDD scores (HDDS) based on the plot and household survey data for 2020. In the survey, the households were asked if they consumed any of the following 12 food groups in the last 24 h; cereals, roots and tubers, vegetables, fruits, meat and poultry, eggs, fish and seafood, legume and nuts, oils and fats, sugar and honey and condiments. All the consumption frequencies of the food items were summed; scores ranged from 0 to 12, with higher scores indicating better HDD. HDD is highly correlated with caloric and protein adequacy, improved birth weight, child anthropometric status, and improved haemoglobin concentrations (Swindale and Bilinsky, 2006).

Months per year of food insecurity, used to assess the frequency of household food insecurity and the months these incidents occur (Musumba et al., 2017), were calculated from the plot and household survey of 2020. Farmers had been asked whether they experienced inadequate food to feed the household and the number of months in which they incurred this incident within one year.

Nutrients (protein and Zinc) contained in the harvested crop were estimated from the crop production data and their concentrations, obtained from laboratory analysis (at IITA for maize and common beans) and USDA database (for pigeon peas; https://fdc.nal.usda.gov/). The protein and Zinc were selected because of their relevance to nutrition within SSA. The concentrations were multiplied by the harvests of the respective crops and then summed up. Daily requirements for each variable were used to derive annual requirements to assess the level of adequacy from the production systems. Due to the importance of legumes to nutrition, the assessments compared cereal grown alone and in intercropping with legumes, across ISFM components.

2.1.5. *Social domain*

The data used to assess social domain indicators were from the plot and household survey of 2020. We focus on the ISFM components and ISFM combinations used by men and women on their separately or jointly managed plots. Gendered differences in the application of soil fertility measures are explored in terms of underlying resource inequities (Marenya and Barrett, 2007; Zhang et al., 2021). Inherent resource inequities between men and women and not gender per se play a big role in the adoption of improved ISFM practices in Kenya (Marenya and Barrett, 2007). Presenting ISFM interactions in the social domain, we not only build upon this insight, but also make use of a conceptual framework that Zhang et al. (2021) developed for the investigation of gender and soil health management. Men and women farmers jointly or separately manage agricultural plots with varying amounts of shared or individual labor, differential access to resources, and decision-making and control rights – all of which may affect soil fertility outcomes and the intra-household allocation of benefits. Since a larger portion of women in Tanzania who manage their plots alone are widowed, divorced, or separated (UN Women, 2015), we have added woman-headed households to further differentiate the analysis. Apart from that, labour requirements receive specific attention and how they increase with the number of ISFM components.

A literature review was conducted and published data on various indicators influenced by ISFM components identified to complement data obtained under the study, across all the domains. In cases such as effects on environment where recent syntheses were available, references to these syntheses are made. In the other cases, a more detailed literature review conducted focusing on studies within SSA, assumed to be similar to conditions in Tanzania. The review ensured that several representative studies covering different geographies are captured. These are presented in Tables otherwise as text through the manuscript. Since these are to complement data from the study sites, the literature review does not represent a full synthesis of all the studies that may be available.

2.2. *Data analysis*

Data obtained were analysed with respect to implementation (presence or absence) of the five identified ISFM components and also on the specific component combinations. For each plot whose data are used, the presence or absence of each of the five components was recorded ('1' if in use and '0' if not in use), and the scores were summed up. The more the ISFM components used within a plot, the more the overall score. Using these data, a range of descriptive statistical tools were used in the analysis (e.g., histograms, cross-tabulations, and box plots) to understand the distributions of the extent of ISFM implementation by farmers in the intervention AEZs in Tanzania. For each site, the percentages of farmers implementing a particular ISFM component were calculated as a proportion of the total farmers in the site.

The analysis of crop productivity data was done in two steps. In the first step, yield data for the first seasons (2012 and 2013) for the sub-humid environment were compared across the number of ISFM components implemented. This was to provide the effect of the number of ISFM components on seasonal productivity. The analysis was done in R statistical software, where the means were calculated, and the bootstrap confidence limits (95% confidence intervals) estimated using the package Boot (https://www.r-project.org/). Statistical comparisons of yields from the components and component combinations was done using Tukey HSD (honestly significant difference) test based on $P < 0.05$. Comparisons between groups are provided when the number of observations was at least 30 plots. It was not possible to combine data from different seasons and sites without standardization, leading to a second stage of analysis. This was necessary to circumvent the challenge of seasonal differences in yields that would skew means for specific management if the number of observations was high/low for a season with high/low yield. Thus, all data were converted into a ratio by dividing reported/observed yield with the attainable yield for that agro-ecology and specific year. The attainable yield is the highest yield within the particular dataset. The ratio to the attainable yield, referred here as relative yield, is a meaningful measure as it indicates how far the yield under particular management is from the attainable yield. The subsequent analysis was done in R by obtaining means and constructing their confidence limits, and comparisons of means using Tukey as stated above.

Gross margins, whole-farm incomes, months of food insecurity, and HDDS were analysed separately for each site and season. The means for each of these and their corresponding standard deviations from the mean were constructed using the summarySE function in R where also the graphs were plotted using package ggplot2. For each case, the associated number of observations was summed up and provided as part of the results. Also, an overall analysis with all the observations of the household survey (i.e., combined whole-farm income per capita data for sub-humid and semi-arid) was conducted with Tukey HSD to determine whether there were significant differences among the ISFM components. The number of observations for groups compared was minimum of 30 except where stated otherwise, e.g. with household survey 2020 under human and social domain where this was the only available study.

Cumulative probability distributions of protein available to farmers were built in R. Also, box plots showing distributions of Zinc harvested in produce were constructed in R.

3. Results and discussions

3.1. *ISFM implementation and its influence on the productivity domain*

Under farmer practices, the number of ISFM components used by farmers varies from 0 to 4 in both sub-humid and semi-arid AEZs. About 50% of farmers implement 1 or 2 ISFM components in sub-humid while 38% of farmers in semi-arid AEZ do not implement ISFM (Figs. 2 to 4). Therefore, both AEZs present huge opportunities to increase ISFM use.

The use of ISFM is more in the sub-humid, a medium to high potential agricultural zone, than in the semi-arid zone of low to medium agricultural potential. Farmer that do not apply ISFM in sub-humid AEZ are only 2% but up to 60% in semi-arid AEZ. In sub-humid AEZ, 95% of farmers use improved maize seeds compared to 11% in semi-arid AEZ. High use of improved maize seeds in the sub-humid zone has been reported previously (Kihara et al., 2015; Mugi-Ngenga et al., 2021). Even for manure application, 55% of farmers apply in sub-humid while only 21% apply in semi-arid AEZ. Fertilizer use is low in both AEZs with only 2 farmers (or 1.2%) observed in semi-arid and 13% in sub-humid AEZ in 2020. A previous survey of 2013 observed an average of 3% fertilizer use among farmers in the sub-humid AEZ (Kihara et al., 2015). In general, about 40% of farmers apply SWC practices both in AEZs. In Sub-humid zone, the proportion of farmers using SWC practices are increased for the category of highest ISFM components (91% under 3 ISFM components in sub-humid). On the contrary, no farmers (0%) were implementing SWC as the only ISFM component in sub-humid, unlike the semi-arid AEZ. High productivity due to a more favourable agricultural production environment in sub-humid AEZ is likely the reason for the higher use of some of the ISFM components such as improved

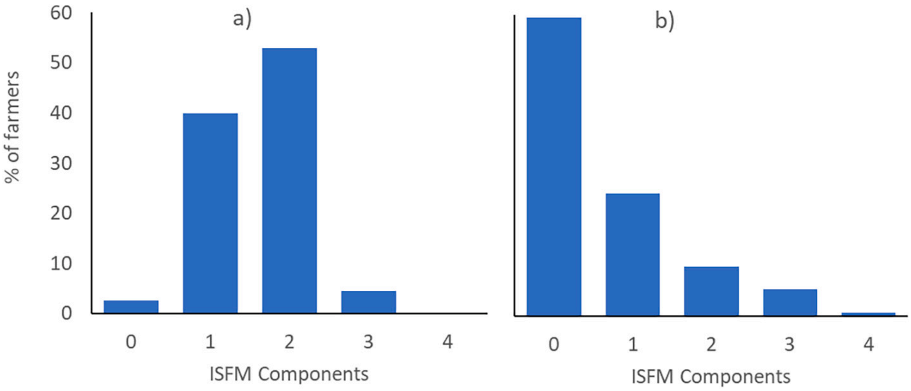

Fig. 2. Distributions of application of ISFM components among farmers in a) sub-humid AEZ ($n = 873$) and b) semi-arid AEZ ($n = 131$). For sub-humid AEZ, data are derived from 5 surveys conducted in 2013, 2014, 2016, 2017, and 2020. For semi-arid AEZ, data are from 2020 survey.

varieties, unlike the semi-arid low productivity AEZ. Farmers apply practices where they stand better chances of getting expected results relative to conventional practices. Factors identified to influence adoption of ISFM include access to improved seeds, labour, off-farm occupation, livestock ownership and plot-level variables such as soil carbon, soil texture, slope and plot area (Adolwa et al., 2019a). Both AEZs have a similar share of cultivated land to maize (51%) but higher food insecurity, poverty levels, illiteracy and agricultural shocks of droughts and flooding are reported for the semi-arid relative to the sub-humid zone (Charles et al., 2016). Although data for the semi-arid zone are from one survey, the site, like the sub-humid zone, is characterized by one long growing season and farmers mostly grow crops based on household decision, i.e., there is no specific season for a certain crop or specific ISFM implementation by farmers. Also, the other cereals in the region, i.e., millet and sorghum, are mostly managed the same way as maize. However, if specific rotational systems are followed or crops grown based on agro-advisory, the implementation of ISFM may vary by season.

Increasing the number of ISFM components is associated with increased maize grain productivity as observed in sub-humid AEZ in 2012 and 2013 (Fig. 3). In 2012, comparing both 1 and 2 ISFM components, both with at least 30 observations, the 2 ISFM components had 45% higher yield ($P < 0.05$) than fields with only 1 ISFM component. Considering the specific components, the yield under improved varieties ($n = 38$) in 2012 are somewhat increased (ns) when also manure ($n = 43$) are added (data not shown). The application of improved variety (36%) and improved variety+manure (44%) were the most common ISFM practices among farmers. No significant differences were observed in 2013. In the two seasons, farmers with 3 components of ISFM (Fertilizer + ImprVar + Man_Appl) had the highest yields, although these were very few. Only 2 farmers had 3 components in 2013 because fertilizer use was very low (Kihara et al., 2015).

Increasing ISFM components from 1 to 2 significantly increased the relative yield, from 0.29 to 0.3.4 in Sub-humid AEZ but were insignificant in semi-arid AEZ ($P < 0.01$; Fig. 4 a, b). Beyond counting the number of ISFM components, the specific components and their combinations revealed more specific contributions to relative yield (Fig. 4 c, d). Improved varieties combined with manure application (ImprVar + Man_Appl) significantly increase relative yields over improved varieties (ImprVar) in sub-humid zone. Applying ImprVar + Man_Appl + SWC and ImprVar + SWC only resulted in low median relative to ImprVar + Man_Appl but means are not statistically different. Preferential application of practices such as SWC to sloppy fields of low soil fertility fields can result in the low medians. This may explain also the low relative yield under 3 ISFM since 93% of the fields in this category had SWC. In Semi-arid AEZ, applying 0 or 1 ISFM components results in the same yields (no significant differences). However, ISFM benefit on yield responses is observed with 3 ISFM components that combine improved varieties, manure application and SWC although only few farmers applied these. In this AEZ, moving from no ISFM component to manure application or SWC components did not result in increased maize yield. Only combination of SWC with improved varieties or improved varieties and manure seem to confer benefits. The benefits of applying organic inputs and SWC support crops to utilize better the different weather conditions through water conservation, enhanced fertility e.g., SOC, and mulching effect (Bationo et al., 2007). Farmers' preferential management such as application of nutrient inputs e.g., manure or implementation of SWC to the more deserving fields and not other fields (Chikowo et al., 2014), and the fact that local varieties often have low nutrient agronomic efficiency (Vanlauwe et al., 2011) could explain the lack of manure or SWC benefits over the no-ISFM in one or both sites. The effects of ISFM on yield are observed all over SSA (Vanlauwe et al., 2010). Survey and multi-locational studies involving a large number of farmers across different environments are probably the best representation of the yield gains observed by farmers. Kabambe et al. (2018), using responses from 44 sites in Malawi, observed yield benefits of maize varying from 40% to 220%, following increased ISFM intensity (improved varieties, groundnut residues incorporation, and fertilizers). In our case, combined improved varieties and manure in semi-humid, and further combination with SWC in semi-arid are supporting increased productivity.

3.2. *Effects of ISFM on the economic domain*

As with productivity, gross margins generally increase when manure is combined with improved varieties (Table 2). Overall in the sub-humid zone, ImprVar + Man_Appl had significantly greater gross margins than the ImprVar and ImprVar + Man_Appl + SWC. This results from consistently improved gross margins for ImprVar + Man_Appl during specific studies/years, being significantly greater than ImprVar in 2016 (farmer recall data). Except for 2016 in farmer-managed trials and 2013 where no benefits were observed, combined manure and improved varieties increased gross margins over improved varieties alone by between US$ 73 to US$ 204 in the sub-humid zone. Thus, for the sub-humid zone, improved varieties combined with manure application are key to achieving increased gross margins. Although increases in gross margins are observed with ISFM as indicated, it is not always that more components result in more gross margins such as where SWC was applied over improved varieties and manure, again likely due to targeted SWC under specific conditions of sloping fields. Such fields are often of low soil fertility. Also, an SSA-wide study (Sileshi et al., 2019) shows the profitability of organics together with chemical fertilizers is the same as that of either component. Similarly, in a study by Hörner and Wollni (2022) in Ethiopia, the adoption of organic fertilizer and improved seed resulted in the highest net crop income as compared to the adoption of all the ISFM components. This was partly attributed to

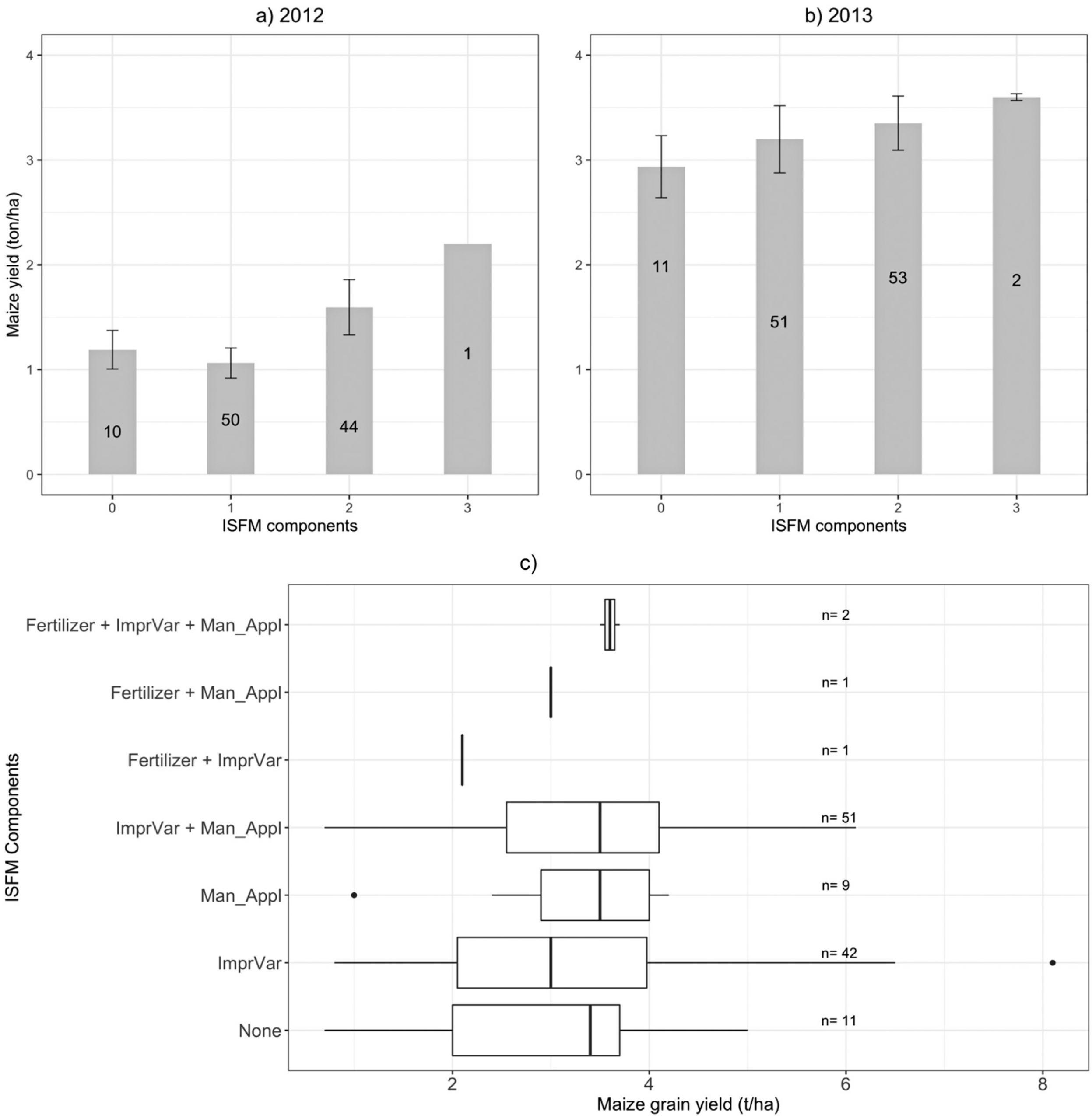

Fig. 3. Effects of the number of ISFM components used by farmers on the yield of maize in Sub-humid AEZ in 2012 based on farmer recall (a) and 2013 based on yield cuts (b), and distributions of maize grain yield under various ISFM component combinations during the 2013 cropping season in sub-humid AEZ, Northern Tanzania (c). Error bars in a and b are confidence intervals. The recall data are from surveys conducted in 2013. Recall yields are generally lower, likely due to seasonal differences or farmer underestimations. The number within the graphs are number of observations. ImprVar = improved variety, Man_Appl = manure application.

the high cost of inorganic fertilizer. In another study conducted in Kenya, Adolwa et al. (2019b) found that net maize income was not significantly different at different adoption levels of ISFM, even though the use of any combination of two ISFM components, or where farmers used any combination of three ISFM components significantly increased maize yields.

As with plot-level gross margins, the net whole-farm income per capita in Table 2 increased (not significant) under improved varieties plus manure compared to improved varieties alone. Net whole farm income includes all income streams on the farm, including income from all crops, crop residues, livestock, and livestock products, less all costs. Farm incomes increase only slightly as the number of ISFM components increases.

The increase in gross margins and somewhat whole-farm income with ISFM is despite the associated increases in labour as demonstrated in several studies (Woomer et al., 2004; Waddington et al., 2007; Rusinamhodzi et al., 2012; Hörner and Wollni, 2022). The increase in costs associated with ISFM can hinder the uptake of ISFM by farmers. However, the returns in our study were sometimes still high enough and compensated the increased associated labor costs. But also, we are cognizant that inequities between men and women farmers in resource access and control may result in gender disparities in adoption rates and income (Marenya and Barrett, 2007; see social domain).

Several other studies have estimated the effect of the adoption of single practices and their combinations on household income (Table 3). While the components can increase yields significantly, these may not

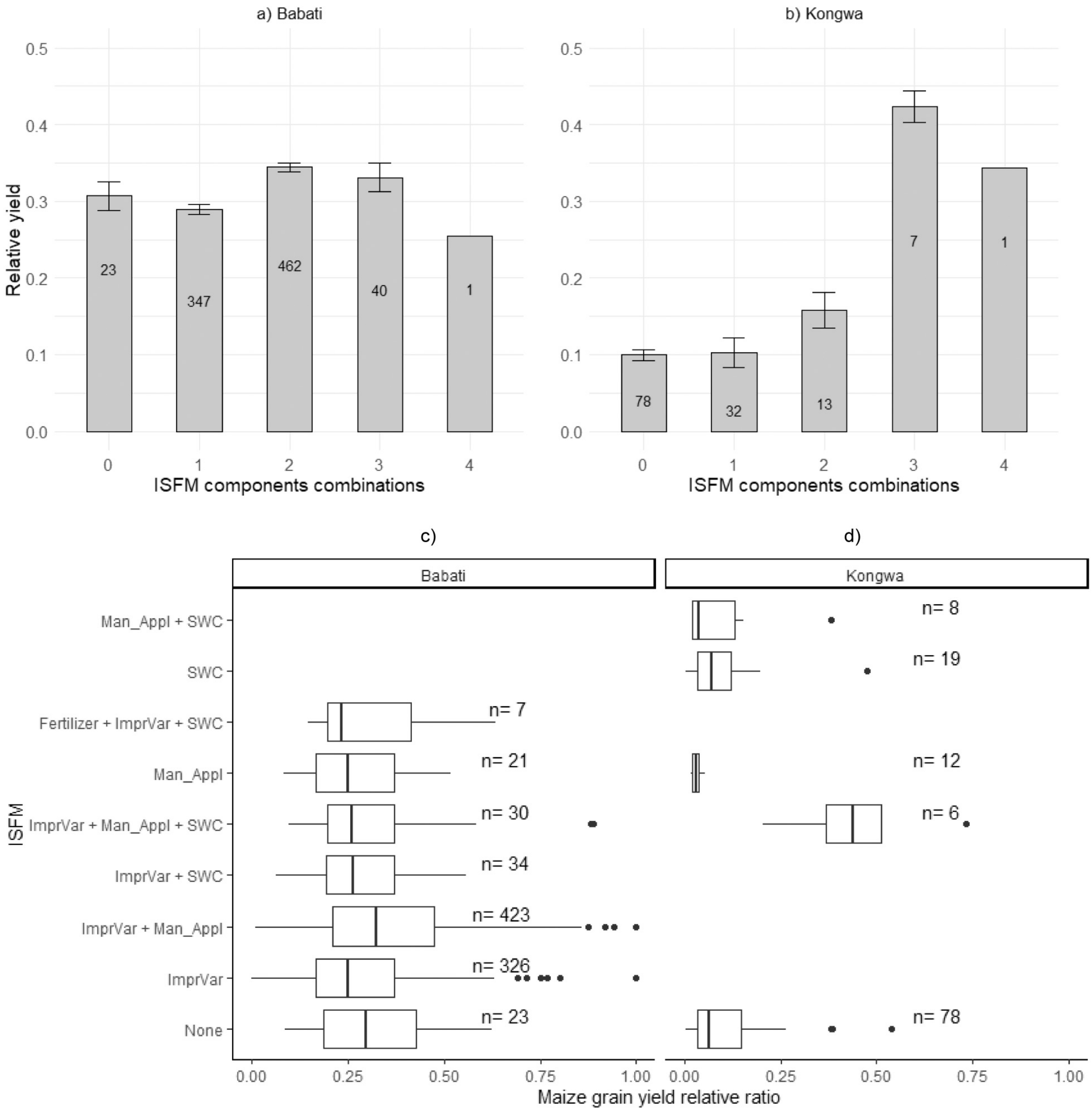

Fig. 4. Relative maize grain yield observed for different ISFM components in Sub-humid AEZ based on data collected during 2012 to 2020 (a) and Semi-arid AEZ in 2020 (b) and distributions of maize grain yield relative yields under various ISFM component combinations across the two AEZs (c, d). Data used are those from farmer practices. The number of observations for each set of ISFM components is shown. Cases where number of observations are very low (<6) are not shown in boxplot. ImprVar = improved variety, Man_Appl = manure application, SWC=Soil and water conservation.

always have a significant effect on household income as observed in Kenya and Ghana (Adolwa et al., 2019b). Also, Noltze et al. (2013), in their study in Ghana, found no significant effect on the household income of system of rice intensification (SRI) adopters compared to non-adopters. However, Wainaina et al. (2018), Manda et al. (2016), Kotu et al. (2017), and Hörner and Wollni (2021) have observed significant effects of individual or combined ISFM components on household income, similar to the net-whole farm economics shown above. Following such increases in household income, Sanka et al. (2016) show that the adoption of ISFM increased household per capita expenditure, translating into a 32% increase in purchasing power.

3.3. *ISFM effects on the environment domain*

Soil organic carbon (SOC) is an important indicator measured in the current study in relation to the environment domain of sustainable intensification. Based on 210 farmer practice plots in 2017, SOC was the same under Improved variety (1.33%) and Improved variety+ manure (1.36%; Table 4). However, the addition of manure to improved variety increased active carbon by 11% from 284 mg/kg under the Improved variety (not significant). With only improved variety, both active carbon and SOC decrease sharply with slope. However, such decrease in carbon by slope is eliminated with application of manure (ImprVar+Man_Appl). Landscape-level processes such as soil erosion and deposition are usually highly correlated with topographic position (Seibert et al., 2007; Jones et al., 2000). But ISFM practice of manure application interacts with

Table 2
Effects of ISFM components used by farmers on the gross margins (US$/ha) and on net whole farm income (US$/ca) for different years in Sub-humid zone and for 2020 in semi-arid zone.

ISFM Component combinations	Farmer recalls 2012	Survey 2013	Farmer recalls 2016	Farmer-managed trials 2016	Farmer-managed trials 2017	Plot and household survey 2020 Sub-Humid	Overall averages for Sub-Humid	Plot and household survey 2020 Semi-Arid	Plot and household survey 2020 Sub-Humid	Plot and household survey 2020 Semi-Arid
	Gross margins (US $ hectare^{-1} season^{-1})								Whole farm net income (US $ capita^{-1})	
ImprVar	190 ± 166	583 ± 311	1056 ± 754b	851 ± 367	802 ± 417	359 ± 237	738 ± 562b		96 ± 94	
ImprVar + Man_Appl	264 ± 287	582 ± 244	1260 ± 680a	646 ± 318	905 ± 399	518 ± 375	892 ± 595a		129 ± 190	
ImprVar + Man_Appl + SWC						521 ± 441	588 ± 374b		95 ± 96	
ImprVar + SWC				801 ± 425			646 ± 429ab			
SWC								90 ± 112		6 ± 13

Note: The numbers after ± are standard deviations. Numbers in the same column followed by different letters are significantly different ($P < 0.05$). Values contain at least 30 (maximum 152) observations (farmer plots) except for overall average gross margins for sub-humid where number of observations are the same as those in Fig. 4, i.e., up to 423. ImprVar = improved variety, Man_Appl = manure application, SWC=Soil and water conservation.

Table 3
Overall economic benefits associated with ISFM practices as observed in different studies. RT = residue retention; IV = improved variety; SWC = soil and water conservation.

Source	Metric and observed Change from normal practice	Specific activity	Systems under comparison
Adolwa et al. (2019b)	No significant change	Any combination of two ISFM components	Maize in Kenya and Ghana
	No significant change	Improved seeds, organic resources, inorganic fertilizer and SWC	
Komarek et al., 2018	+75% in economic profits	Organic resources	Malawi
Wainaina et al. (2018)	+US$ 420 in HH income	IV and organic manure	Kenya
	+US$ 573 in HH income	IV and zero tillage	
Manda et al., 2016	Household income per capita		Zambia
	+54%	IV (maize)	
	+75%	IV (maize) and RT	
	+69%	IV (maize)	
	+43%	IV (maize), RT	
Khonje et al. (2018)	+289ZMW	Zero tillage	Zambia
	+447ZMW	IV (maize)	
	+914ZMW	IV (maize) and zero tillage	
Hörner and Wollni (2021)	+32% in household income per capita	IV with either organic and/or inorganic fertilizer	Ethiopia

Table 4
Active carbon and soil organic carbon (SOC) observed under ISFM components in sub-humid Zone during the 2017 cropping season.

ISFM Components	Depression	Very gentle	Gentle	Sloppy	Average
Active Carbon (mg/kg soil)					
ImprVar		326 ± 219	264 ± 215	228 ± 179	284 ± 210
ImprVar + Man_Appl	311 ± 140	334 ± 184	316 ± 200	272 ± 156	315 ± 182
SOC (%)					
ImprVar		1.54 ± 0.42	1.23 ± 0.36	1.08 ± 0.43	1.33 ± 0.43
ImprVar + Man_Appl	1.68 ± 0.43	1.33 ± 0.43	1.35 ± 0.40	1.16 ± 0.51	1.36 ± 0.44

Sloppy fields have between moderate to steep slope. Data are shown where n varied from 13 to 33 for specific landscape positions. For the overall average, *n* = 67 for ImprVar and 115 for ImpVar+Man_Appl. ImprVar = improved variety, Man_Appl = manure application.

slope position, i.e., the contribution to SOC by increasing ISFM is influenced by slope position of the field. Fourty 8 % of farmers apply manure annually, on average 3.5 t ha^{-1}, while 36% do not apply and the rest apply only in some seasons (Kihara et al., 2015).

Environmental benefits such as soil loss reduction through local adaptation of farm fields, for example, through insitu water harvesting using furrows and tied ridges, have been reviewed previously (Kihara et al., 2020; Fig. 5). The presence of this component of ISFM reduces soil loss by 40 to 80% relative to conventional systems, translating to 5 to 20 t ha^{-1} yr^{-1} in the case of Araya et al. (2011). The reductions are also associated with a 25 to 70% reduced runoff and 45 to 90% increased infiltration (Kihara et al., 2020) reduced nutrient losses. The magnitudes of soil loss reduction or infiltration are highly likely influenced by local

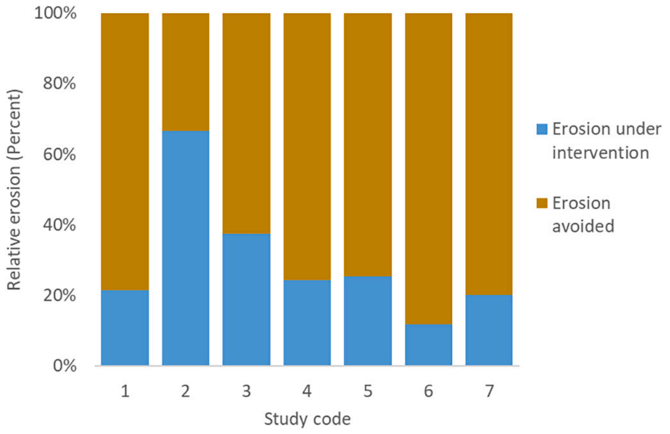

Fig. 5. Erosion avoided due to local adaptation/ISFM (in-situ water harvesting and CA) practices in SSA (adapted from Table 1 in Kihara et al., 2020). "Study code" is an individual study for a specific location. Erosion avoided is calculated as the erosion without intervention minus erosion with intervention.

soil and weather factors hence the need to understand them within the local contexts. In Zimbabwe, for example, the use of tied ridges and furrows reduced runoff-based nutrient losses (N and K) by over 300% (Munodawafa, 2007). However, erosion control is hindered by 'women's lower access to resources and information on soil and water conservation and by male-dominated decision-making on agricultural land (Tenge et al., 2004).

Fertilizer application contributions to the environment domain relating to leaching and greenhouse gases were not measured in the current study but reviewed previously by Kihara et al. (2020). Based on the scanty data observed for SSA, the amounts of N leached vary from nil to over 250 kg N/ha yr^{-1}, influenced mainly by fertilizer (application and also the amounts) among other factors such as rainfall amounts, soil types, and accompanying practices such as residue inclusion. Managing the application rates and local adaptation practices can minimize the leaching tradeoff of fertilizer use. Other researchers have observed ISFM (combination of manure and nitrogen fertilizer) to increase nitrogen uptake, e.g., by 100% over the nitrogen fertilizer uptake only treatment in seasons of application and residual seasons maintaining productivity while minimizing leaching (Nyamangara et al., 2003). These benefits are based on additive ISFM, and Sileshi et al. (2019) showed that even more significant benefits in nutrient use efficiencies are obtained with substitutive ISFM. Manure minimizes leaching relative to synthetic mineral nitrogen (Kihara et al., 2020; Kamukondiwa et al., 1996). Combining fertilizers and organic inputs is associated with immobilization and mineralization processes that synchronize with plant nutrient uptake, reducing losses to the environment (Chivenge et al., 2009). Also, alternative strategies such as legume integrations support biological nitrogen fixation and reduce dependence on chemical fertilizers.

Improved varieties, as a component of ISFM, have increased nutrient use efficiencies compared to local varieties (Vanlauwe et al., 2011), indicating better utilization of available resources. The often increased productivity results in increased biomass that, with good tradeoffs, can be targeted for mulching as an organic input to the production system.

3.4. *ISFM effects on the human condition domain*

The two main indicators of the human condition, namely food security and nutritional benefits, are used in this study to evaluate the influences of ISFM.

3.4.1. *Effects on food security*

Household food insecurity is, on average 1.0 (range 0 to 3.14) and 2.76 (range 0 to 10.5) months in Sub-humid and Semi-arid AEZs, respectively; and are lowest at the highest ISFM components (Table 5). Adding manure to improved varieties reduced months of food insecurity from 1.4 to 0.95 in sub-humid while still further addition of SWC almost eliminated food insecurity (i.e., 0.4 months). In the semi-arid zone, the use of either manure or SWC did not reduce but rather manure use even significantly increased months of food insecurity compared to the no-ISFM. Being the only dataset providing food security indicators, comparisons are presented for component combinations with at least 10 observations. A significant increase in months of food security is not expected with manure application over no-ISFM. Also, an increased off-farm income of only US$ 10 observed at no-ISFM in the Semi-arid zone does not fully explain their low food insecurity. This presents a research gap that needs to be addressed.

Table 5
Months of food insecurity and Household dietary diversity scores (HDDS) by ISFM in Sub-humid (a) and Semi-arid zones (b) in Tanzania. Values after "±" are standard deviations.

ISFM components	Months of food insecurity	HDDS
Sub-humid zone		
ImprVar	1.42 ± 2.8a	6.12 ± 1.4a
ImprVar + Man_Appl	0.95 ± 2.9a	7.42 ± 1.9b
ImprVar + Man_Appl + SWC	0.4 ± 1.5a	7.27 ± 1.1ab
ImprVar + SWC	1.83 ± 3.6a	8 ± 1.5b
Semi-arid zone		
No-ISFM	2.14 ± 3.2a	5.94 ± 1.9a
Man_Appl	8.42 ± 3.9b	5.33 ± 1.9a
SWC	3.25 ± 2.9a	6.75 ± 1.4a

Only component combinations with at least 10 observations are shown. ImprVar = improved variety, Man_Appl = manure application, SWC=Soil and water conservation.

3.4.2. *Effects on nutritional requirements*

Farmers who used more ISFM components in the Sub-humid AEZ achieved higher mean HDDS (see Table 4 above). Adding either manure or SWC to Improved varieties significantly increased HDDS. Elsewhere in Tanzania, the combined use of organic and inorganic fertilizers (with or without intercropping) has been associated with an increase in child nutritional status (Kim et al., 2019).

Other studies consider Household Food Insecurity Access Score (HFIAS) where households with lower HFIAS are considered food secure (Coates et al., 2007; Diallo et al., 2020). Based on HFIAS scores of 2.92 relative to 3.31, adopters of ISFM (use of improved seeds and fertilizers) are more food secure than non-adopters in Sub-humid Tanzania (Sanka et al., 2016). Similarly, in Ethiopia, in a humid region, adopters of ISFM (using improved seeds, organic and inorganic manure) had an HFIAS of 0.18, compared to 0.33 for non-adopters, but no change was observed for a dry region where crop growth was impeded by climatic conditions.

The practice of various components of ISFM also influence the concentration of important nutrients in edible crop parts and thereby human and animal nutrition. For example, combined applications of organic resources and chemical fertilizers (for N and P) increased the concentration of grain Zn in Zimbabwe (Manzeke et al., 2017).

While it can be expected that increasing ISFM components is associated with increased human nutrition such as better child growth indices, there are no studies showing this association. The increasing agricultural intensification e.g., through more ISFM components, leads to more available food and nutritional security, but the concomitant increased labour requirements can take away these gains, i.e., negative effects on human nutrition as observed with body mass index in Tanzania (Komatsu et al., 2019). This is especially true if options for reducing drudgery e.g., through draft power, are not available or cannot fit into cropping system in use. Furthermore, age- and gender-differentiated outcomes of ISFM on nutrition, and food security constitute an important overlap of the human condition and social domain and require further research.

Summary benefits of ISFM components on human nutrition indicators in different regions as discussed above are summarized in Table 6. Key practices constituting ISFM components identified in these studies as responsible for the increases in food security include improved varieties, e.g., improved maize (Kassie et al., 2014; Manda et al., 2018; Dibba et al., 2017), and a combination of farmyard manure and inorganic fertilizers (Wanyama et al., 2010).

3.5. *ISFM interactions in the social domain*

Results in Table 7 indicate that in MHHs, manure was the most adopted ISFM component on woman-managed plots (55.6%), and SWC technologies on man-managed plots (46.7%). In contrast, most woman-managed plots in WHHs used SWC technologies. Considering the order of the three most used approaches, the percentage of farmers with no ISFM management was more than those who adopted the ISFM components, with the highest rate for plots in WHHs (51.9%) and woman-managed plots in MHHs (44.4%). Plots run by women managers in MHHs and WHHs were likelier to have manure and SWC as a single ISFM component than plots managed by men. Women managers concentration on no-ISFM or only one ISFM component could be due to labor

Table 6
Effects of ISFM adoption on household food security (e.g. months of food security) and nutritional security. All the systems reported were under farmer management. HFIAS = Household Food Insecurity Access Score.

Source	Region	Crop	Measure of food security	Without ISFM	With ISFM	ISFM System used
Wanyama et al. (2010)	Kenya	Maize	No. of months with food	3.8	7.1	Organic + inorganic fertilizers
		Beans		1.8	6.2	
		Finger millet		3.4	6.2	
		Groundnuts		0.9	6	
		Sweet potatoes		4.0	5.9	
		Sorghum		6.6	7.6	
		Vegetables		2.6	7.6	
Kristjanson et al. (2012)	E. Africa		No. of months with food	<4	>4	Not defined
Tambo and Wünscher (2017)	Ghana		No. of months with food	8.12	9.4	Not defined
Sanka et al. (2016)	Tanzania	Maize and pigeon peas	HFIAS	3.31	2.92	Improved seeds + organic + inorganic fertilizers
Hörner and Wollni (2021)	Ethiopia	Maize, wheat and teff	HFIAS	0.33	0.18	Improved seeds + organic + inorganic fertilizers
Hörner and Wollni (2021)	Ethiopia	Maize, wheat and teff	HFIAS	0.27	0.25	Improved seeds, organic + inorganic fertilizers
Diallo et al. (2020)	Mali	Maize	Food secure households (%)	22	78	Organic resources
Dibba et al. (2017)	The Gambia	Rice	Food secure households (%)	43.5	59	Improved seeds
Kerr et al. (2019)	Malawi	Maize, cowpea, and groundnuts	Food secure households (%)	21	28	Organic resources

Table 7
Most used ISFM components and ISFM approaches by gender of manager and household type (in the percentage of plots) averaged across sub-humid and semi-arid AEZs as observed in 2020. N denotes the number of plots. In MHHs, plot sizes (mean) ranged between of 1.2 ha for men, 0.7 ha for women, and 1.1 ha for jointly managed plots. Women heads had an average of 1.6 ha at their disposal.

	Man-headed households						Woman-headed households	
	Man-managed plots (N = 107)		Woman-managed plots (N = 79)		Jointly-managed plots (N = 116)		Woman-managed plots (N = 27)	
Three most used ISFM components (alone or in combinations)	SWC	46.7%	Manure	55.6%	Improved varieties	51.7%	SWC	33.3%
	Improved varieties	45.0%	Improved varieties	22.2%	Manure	36.2%	Improved varieties	25.9%
	Manure	31.7%	SWC	11.1%	SWC	29.3%	Manure	22.2%
Three most used approaches (0 to 4 ISFM components)	No ISFM (0 component)	36.7%	No ISFM (0 component)	44.4%	No ISFM (0 component)	30.2%	No ISFM (0 component)	51.9%
	Improved varieties, SWC (2 components) or Improved varieties, SWC, manure (3 components)	13.3%	Manure (1 component)	33.3%	Manure, improved varieties (2 components)	14.7%	SWC (1 component)	14.8%
	SWC, manure (2 components)	8.3%	Manure, improved varieties (2 components) or Improved varieties, SWC, manure (3 components)	11.1%	Improved varieties (1 component)	12.1%	Improved varieties, SWC, manure (3 components) or Improved varieties (1 component)	11.1%

constraints in WHHs, especially lower access to male adult household labor (UN Women, 2015). The fact that men managers in man-headed households (MHHs) more frequently indicated combinations of at least three components than women managers especially those of woman-headed households may relate to a larger labor force in this household type.

Improved varieties constituted an important ISFM component for plots in MHHs that men farmers manage exclusively (45.0%) or with a spouse (51.7%). They were almost always applied in combination with other soil fertility measures. In contrast, women in MHHs and WHHs ranked improved varieties lower among the most used components. This may be explained by women's lower income (or in MHHs, lower access to and control of household income) as compared to men as established in other surveys for semi-arid and sub-humid AEZs (Fischer et al., 2021; Fischer et al., 2020). For MHHs, higher levels of male income control may well be associated with men's preference to purchase improved seeds for plots on which they have more input in decisions on how yields are used. In the survey, 26.9% of the respondents in MHHs indicated men to have sole income control, 14.2% reported women to have sole control and 59.0% saw husband and wives as sharing income control (data not shown). Recent studies warn that the response variables "joint" or "shared" need to be read with caution and do not automatically denote equal input in decisions. For instance, Acosta et al. (2020) unpack the meaning their respondents assign to "joint decision-making" and find that the term is also understood as discussions in which women's ideas are heard, but men have the final say. The finding that men use higher amounts of improved seed (as compared to women plot managers) is in line with Makate and Mutenje's (2021) results for Tanzania. There were no statistically significant differences between the three respondent groups regarding extension services received and the perceived usefulness of extension advice (results not presented).

SWC technologies (as a component) are frequently employed in man-managed than woman-managed plots of both MHHs and WHHs. Besides labour availability, this imbalance may be based on predominantly male land ownership in Tanzania (Tenge et al., 2004). Women in MHHs may be reluctant to invest in these technologies because of low tenure security (Zhang et al., 2021). On the other hand, women managers in MHH more frequently recorded manure application on their plots (55.6%) than other plot managers (36.2% for jointly managed plots, 31.6% for man-managed plots and 22.2% for plots managed by women in WHHs). This rather counterintuitive result for women in MHHs is confirmed by other surveys in the study area (not published and not used for this paper). Gender differences in manure access and application are an important research question to pursue further. Ndiritu et al.'s (2014) study in Kenya for instance shows that woman-managed plots had a lower application rate for manure. Ndiritu et al. (2014) interpret their finding as potentially associated with the laborious transport of manure to the plots and women's lower livestock ownership and access to manure.

If ISFM is conceptualized to include organic material from crop associations to carve out a holistic picture of gendered soil management dynamics at the household level, crop associations are more commonly applied than manure, alone or in combinations regardless of who manages the plot (Table A1 in the appendix). Plots run by women managers (in both household types) were more likely to have crop associations as a single ISFM component than plots managed by men. In woman-headed households (WHHs), crop associations were in 37.0% of plots, followed by no ISFM management (14.8% of plots) and combinations of two components. Combinations of more than two components ranked very low. The order of the three most used components and approaches in Table 7 for the most part remains the same or shows minor variations even when crop associations are considered.

As expected, labour demand rises with the number of ISFM components for men and women (Fig. 6). Women labour is significantly higher at 3 and at 1 ISFM components than at no-ISFM. Also, for men, labour at 3 components is significantly higher than at all components <3, while also two components have significantly higher labour than no-ISFM (0 components). Total labour follows the same pattern as men labour except that also labour with 1 component is significantly higher than at 0 ISFM (i.e., no ISFM). This underlines that the movement toward adopting more ISFM components can be labor-intensive. The results are consistent with those of other studies, such as Teklewold et al. (2013), who found that combinations increased labour more than the use of a single ISFM component for both men and women in Ethiopia. Beyond component counts, labour was not statistically different across the specific ISFM component combinations, disaggregated by AEZ (Table 8). Nevertheless, applying either manure or SWC attracted additional labour of at least 75% in the semi-arid AEZ and no clear pattern in the semi-humid AEZ. In general, there is more labour applied in sub-humid relative to semi-arid AEZ.

Irrespective of gender, several studies confirm that the adoption of ISFM and related practices increase labor demand (Table 9). Adopting more components of ISFM can invite more labour than the adoption of less components, and both increased labour compared to non-adoption of ISFM (Horner and Wollni 2020). Rusinamhodzi et al. (2012) and Waddington et al. (2007) observed that intercropping increased labor demand during weeding by 36% compared to sole cropping due to increased plant density. The adoption of some practices under ISFM e.g., minimum tillage, can reduce labor requirements (Jaleta et al., 2016) through reduced labor in land preparation and weeding compared to conventional practices. On the other hand, some practices, such as planting basins, are associated with increased labour for their establishment (Rusinamhodzi et al., 2012). The labour reduction, therefore, depends on the context of the application of the local adaptation. Understanding these perspectives is essential since the adoption of ISFM practices is influenced by labour (De Groote and Coulibaly, 1998; Kassie et al., 2011; Kamau et al., 2014; Kassie et al., 2013; Kanyamuka et al., 2020). How ISFM practices relate to women and men's different labor roles and burdens and how they may be increased or reduced to achieve more equity must be part of this effort.

Table 8
Labour under different ISFM components in Sub-humid (a) and Semi-arid zones (b) in Tanzania. Values after “±” are standard deviations.

	Male labour	Female labour	Total labour
Sub-humid AEZ			
ImprVar	46.6 ± 27.7	29.1 ± 25.5	74.8 ± 40.2
ImprVar + Man_Appl	45.2 ± 34.2	23.6 ± 19.0	68.8 ± 42.4
ImprVar + Man_Appl + SWC	49.4 ± 46.8	30.8 ± 33.9	80.2 ± 72.1
ImprVar + SWC	37.9 ± 17.9	23 ± 17.7	60.9 ± 32.8
Semi-arid AEZ			
No-ISFM	23.5 ± 15.1	15 ± 12.9	38.5 ± 21.7
Man_Appl	20.8 ± 11.8	27.7 ± 16.5	48.6 ± 23.4
SWC	21.6 ± 18.5	30.9 ± 36.3	52.5 ± 43.6

Only component combinations with at least 10 observations are shown. ImprVar = improved variety, Man_Appl = manure application, SWC=Soil and water conservation.

3.6. Additional perspectives across domains

The range of plot and household level indicators due to ISFM influences are quite varied. A summary of ISFM component benefits on households is shown in Table 10. Although a good case is provided for Tanzania and from the literature cited, other dimensions, e.g., rural household poverty, may be impacted and not well studied. One study

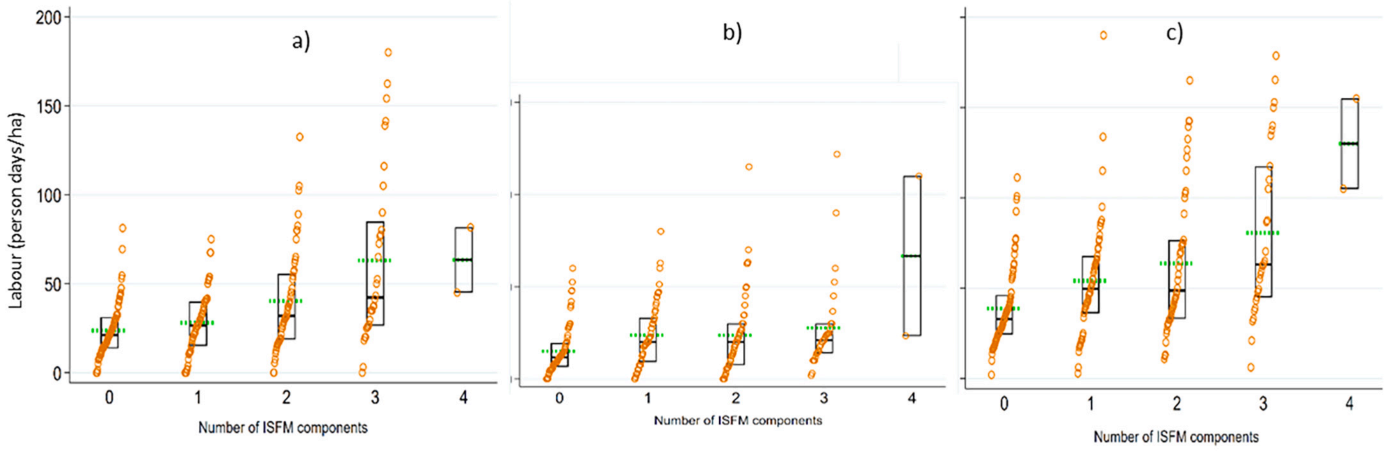

Fig. 6. Distributions of labour by ISFM component for a) men, b) women and c) total men and women in studied sites in Tanzania. The strip plot combines the basic summary statistics of a box plot with the visual information provided by a local density estimator. The median is shown as a black line, and the dashed line shows the mean.

Table 9

Labour changes due to ISFM practices as observed in different studies across sub-Saharan Africa. ND=Not defined.

Source	Observed change from normal practice	Specific activity	Systems under comparison
Hörner and Wollni (2022)	+2 total person-days ha^{-1} (in Amhara)	Overall system	No ISFM vs Improved seeds with either organic and/or inorganic fertilizer
	+25 total person-days ha^{-1} (in Tigray)	Overall system	No ISFM vs Improved seeds with either organic and/or inorganic fertilizer
Rusinamhodzi et al. (2012)	+40% in labor demand	Weeding	No-till planting basins vs conventional land tillage
	+36% in labor demand	Weeding	Intercropping vs monocropping
	from 6 man-days to 15–27 man-days ha^{-1}	Land preparation	Conventional tillage vs planting basins
Komarek et al. (2018)	+58 man-days ha^{-1}	Overall system	Maize-groundnut rotation vs maize monocropping
Woomer et al. (2004)	+20% in labor cost	ND	MBILI vs conventional intercropping
Waddington et al. (2007)	+7.1 man-days ha^{-1}	All activities prior to harvest	maize-groundnut Intercrop vs monocrop maize
Pypers et al. (2011)	+ US$ 122–201 in labor cost ha^{-1}	Germplasm and spacing	Recommended spacing in planting vs traditional planting methods
Jaleta et al. (2016)	- 22.6 (total person-days ha^{-1}) - 14.4 (man-days ha^{-1}) - 8.2 (woman-days ha^{-1}) - 13.2 pair of oxen-days ha^{-1}	Land preparation and weeding	Minimum tillage vs conventional tillage

shows that adopting conservation agriculture and improved maize varieties both in isolation and in combination reduced the probability of rural poverty by 29–40% compared to non-adopters (Khonje et al., 2018). Some of the questions for further research include understanding the proportion of farmers who implement ISFM for specific deliberate goals such as improving soil health, and how the ISFM component effects vary across different soil types. Also, the variability among the specific ISFM practices by farmers, e.g., type and nature of intercropping and reasons behind those, amounts of fertilizer and how that vary for example by use of improved varieties, require further studies.

Our study did not assess if the additional income from ISFM is reinvested into more ISFM, nor whether the saved labour (with less ISFM) and off-farm income are of any spinoff value to the households. Also, where and what level of diminishing returns are observed at increasing levels of ISFM components and what SIAF domains could be compromised if farmers stopped increments of ISFM components is insightful. Indeed, looking beyond just manure and fertilizer application to also amounts of application could perhaps give more insights into trends within or across domains, i.e., the specific ways that ISFM is implemented should be given proper attention. For example, the productivity gains of ISFM depend on the application of good management practices such as timely planting. In Semi-arid AEZ, early planting increased mean yield by 19% to 37% relative to delayed/late planting (data not shown). In Sub-humid AEZ, every day delay in planting reduced maize grain yields by 3 kg/ha relative to early planting (Kihara et al., 2015). While good agricultural practices are important, these have been covered in other studies and were not the focus of our study.

Table 10

Summary of effects of ISFM components on farmers and potential intra-household differences. Organic resources include either crop residues/surface mulches, green manures, fallowing, compost and farm yard manure.

ISFM component	Changes related to specific indicators	Interaction with intra-household differences in men and women 'farmers' (examples)
Fertilizer use	• Increased application labour especially in hill placement and for top-dressing, • Increased yields, • Reduced variability of production, • Increased returns to labour, • Increased risks in case of failure, • New skills required to avoid risks to environment through leaching and greenhouse gases.	• Access to agricultural information • Control of income for fertilizer purchase • Access to benefits from sales • Labor contributions
Soil and water conservation	• High labour demand for establishing conservation structures, • Good returns to labour in long run. • Reduced tillage lowers labour requirements	• Land tenure and decision-making on land and technology use • Labor contributions
Improved varieties	• Increased yields, • increased nutrition in some cases (e.g. with biofortified crops), • increased production resilience when matched with production environment. • High returns on investment.	• Control of income for purchase of improved seeds • Preferences for varieties • Access to seeds
Organic resource$^{¥}$	• High labour demand to transport and apply, • increased yields, • savings from fertilizer purchases, • Increased environmental benefits through extended (over time) soil cover especially with long duration legumes such as pigeonpea	• Livestock ownership (including ownership of manure as by-product) • Control of household labor

4. Conclusions

The benefits of ISFM are observed across multiple sustainable intensification assessment framework domain indicators and increase with increasing ISFM components practiced by farmers. Increased ISFM components are associated with increased labour and increased gross margins/ economic gains that often compensate the labour costs. Farmers in either Sub-humid or Semi-arid and Kiteto did not use all the five components of ISFM considered in this study, with the majority using a maximum 1 or 2 components. There are clear opportunities for increasing the number of ISFM components, since more ISFM comes with more yield, gross margins and nutritional benefits. Although increasing implementation of ISFM by farmers has demonstrated benefits across multiple SIAF domains, it is influenced by socio-economic issues such as affordability and labour demands that need to be addressed through other studies and policy interventions. More attention should be directed to supporting woman-managed households to enhance their adoption of ISFM with more components. Concomitant analyses of ISFM impacts across domains are recommended in future studies that should also address the identified research gaps, especially for data deficient environment and social domains.

Declarations

This work was supported by the United States Agency for International Development (USAID) under grant number AID-BFS-G-11–00002 through the Africa Research In Sustainable Intensification for the Next Generation (Africa RISING) Program as part of the United States Government's Feed the Future Initiative. The study was aligned to the Water Land and Ecosystems CGIAR research portfolio and is fully within the scope of the newly launched Excellence in Agronomy Initiative.

Ethics approval

N/A.

Consent to participate

N/A.

Consent for publication

N/A.

Availability of data and material

The involved scientists provided data for this work, with some already in public repositories.

Code availability

N/A.

Authors' contributions

JK coordinated the whole study. JM contributed household data for 2020 and led aspects around the economic domain. AK provided fertilizer trials agronomic data for semi-arid AEZ for 2016 and background information for this zone. ES contributed to aspects of the environment domain, mostly on soil and water conservation. CM helped with plant analyses and conversion tables used to generate nutrition data. MK supported literature reviews for the different sections of the manuscript, especially on productivity, environment, and economics, including labour. PO contributed during conceptualization and follow-up reviews. GF contributed to the overall conceptual framework but also led the social domain and its cross-cutting discussions. FK contributed to overall conceptualization and linkages of indicators across spatial scales and domains and review of the environment domain. MB conceived the initial idea of a synthesis activity.

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

Data will be made available on request.

Acknowledgements

We acknowledge the team implementing the USAID Africa RISING project who managed trials and collected data on which this work was built. This Include Mr. Stephen Lyimo, Yangole Luhenda and the following staff at the ministry of agriculture, Babati namely; Julius Jonas, Madam Jetrida Kyekaka, Rose Parangyo, Edgar, together with their colleagues at the village and wards including Judith Manzi, Adelta Macha, Ezekiel Mgumi, David Laswai, Boniventus Mutui, Everyline Kaya, Eldar Mmari, Rajab and Mbwabo who all played facilitative role and coordination of activities with farmers. We acknowledge also Mr. Vanance Kangwa for his technical support and driving services and Andrew Sila who supported with Tukey HSD statistical tests.

Appendix A

Table A1

Most used ISFM components and ISFM approaches by gender of manager and household type (in percentage of plots) averaged across sub-humid and semi-arid AEZs as observed in 2020. N denotes the number of plots. In MHHs, plot sizes (mean) ranged between of 1.2 hectares for men, 0.7 hectares for women, and 1.1 hectares for jointly managed plots. Women heads had an average of 1.6 hectares at their disposal.

	Man-headed households						Woman-headed households	
	Man-managed plots (N=107)		Woman-managed plots (N=79)		Jointly-managed plots (N=116)		Woman-managed plots (N=27)	
Three most used ISFM components (alone or in combinations)	Crop associations SWC Improved varieties	81.7% 46.7% 45.0%	Crop associations Manure Improved varieties	100.0% 55.6% 22.2%	Crop associations Improved varieties Manure	75.9% 51.7% 36.2%	Crop associations SWC Improved varieties	74.1% 33.3% 25.9%
Three most used approaches (ISFM intensity)	Crop associations (1 component)	26.7%	Crop associations (1 component)	44.4%	Crop associations (1 component)	15.5%	Crop associations (1 component)	37.0%
	Crop associations, improved varieties, SWC, manure (4 components)	13.3%	Crop associations, manure (2 components)	33.3%	No ISFM (0 component)	14.7%	No ISFM (0 component)	14.8%
	Crop associations, improved varieties, SWC (3 components)	11.7%	Crop associations, improved varieties, manure (3 components) or Crop associations, improved varieties, SWC, manure (4 components)	11.1%	Crop associations, improved varieties, manure (3 components)	13.8%	Crop associations, SWC (2 components) or Crop associations, improved varieties (2 components)	11.1%

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