

**AGRO-ECONOMICS OF CEREAL-LEGUME INNOVATIONS AND THEIR  
INFLUENCE ON FARMER HOUSEHOLD DECISION MAKING AND  
KNOWLEDGE IN BABATI, TANZANIA**

By

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Degree of Doctor of Philosophy in Environmental Sciences and Education in the  
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**DECLARATION**

**Declaration by Student**

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## **DEDICATION**

This work is dedicated to my beloved wife Anne and our lovely daughters: Heidi-hymn and Adelta.

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## LIST OF ABBREVIATIONS

<b>AE</b>	Agronomic efficiency
<b>ANOVA</b>	Analysis of variance
<b>BCR</b>	Benefit to cost ratio
<b>BNF</b>	Biological nitrogen fixation
<b>DUL</b>	Doubled-up legume
<b>GLM</b>	General linear model
<b>ISFM</b>	Integrated soil fertility management
<b>LAI</b>	Leaf area index
<b>LSF</b>	Least significant difference
<b>MBILI</b>	Managing beneficial interactions in legume intercrops
<b>MEY</b>	Maize equivalent yields
<b>NDFA</b>	Nitrogen derived from atmosphere
<b>NP</b>	Net profitability
<b>PAR</b>	Photosynthetically active radiation
<b>PFP</b>	Partial factor of productivity
<b>SI</b>	Sustainable intensification
<b>SSA</b>	sub-Saharan Africa
<b>TVC</b>	Total variable cost
<b>VCR</b>	Value to cost ratio

## ABSTRACT

The robust linkage between soil fertility, food security and smallholder farmer economies unveil the need for developing agronomic innovations that improve soil fertility while ensuring climate resilience of smallholder systems. Introduced innovations should not only be targeted to achieve holistic improvement in cereal-legume productivity but also boost farmer knowledge without compromising the existing gender relations. For this reason, a study was conducted in Babati District of Tanzania guided by the following objectives, to: i) assess the economics of improved cropping systems in Gallapo, Sabilo and Riroda villages of Babati, ii) examine the effect of different cropping systems on biological nitrogen fixation of intercropped legumes, iii) evaluate how different cropping systems influence crop physiological characteristics and soil physical-chemical properties, iv) assess the influence of farmer gender on agricultural-based decisions making involving implementation of improved cropping systems, and v) examine how different socio-economic factors affect farmer knowledge on implementing improved cropping systems. Experimental trials were established to address objectives 1, 2 and 3 while household surveys addressed objectives 4 and 5. Six on-farm trials were set in randomized complete block design replicated three times. Eight treatments were laid on 5 m × 7 m plots comprising different intercropping options under uniform N (50 kg ha<sup>-1</sup>) and P (20 kg ha<sup>-1</sup>) fertilization regime. Cropping systems tested were a business-as-usual and an improved maize-legume system with and without de-topping, sole maize, Mbili-Mbili, doubled-up legume and maize (vertical leaf architecture) intercropped with pigeon pea. Probability proportionate to size sampling was conducted during enrollment of farmers for participatory technology testing. Results indicated that maize equivalent yields of between 2.0 t ha<sup>-1</sup> in sole maize and maize-pigeon pea with no de-topping in 2019 to 12.2 t ha<sup>-1</sup> in doubled-up legume in 2021 season. Mbili-Mbili was stable across seasons and earned more net benefits (US\$ 150; p≤0.01) and highest value cost ratio (8.1; p≤0.001) than other intercropping options. Biological nitrogen fixation indicated pigeon pea to fix between 23–120 kg N ha<sup>-1</sup> depending on site and season. Doubled-up legume had significantly higher and earlier pigeon pea branch and flower development than treatments under maize-pigeon pea system. Male household heads made 50-73% of decisions relating to Mbili-Mbili and 37-66% for doubled-up legume. Decisions on control of incomes were dominated by male household heads (42%), joint decision by male household heads + female spouses (29.5%), female spouses (22.2%) and other household members (7%). Four independent factors i.e., technical, functional, application, and soil fertility had a positive association explaining 71% of variation in farmer knowledge on Mbili-Mbili and 76.5% for doubled-up legume. The most significant socio-demographical drivers of farmer knowledge were age and gender of farmer, household size, distance of plot from homestead, type of farmer engagement, and years of farming experience. In conclusion, Mbili-Mbili is a cropping system with a potential for increasing productivity and climate resilience of smallholder farmers in areas characterized by similar agro-ecological conditions as Babati. However, cheaper mechanization strategy is needed to reduce labor demands which this study identified as the main disincentive for its adoption by farmers.

## CHAPTER ONE: INTRODUCTION

### 1.1 Background Information

Employment of poor soil fertility management practices is a major drawback to sustainability of food production in smallholder farming systems of sub-Saharan Africa (Daudu *et al.*, 2019; Debie *et al.*, 2022). Continuous cultivation with limited soil nutrient replenishment has resulted in nutrient outputs exceeding inputs hence impoverishing the soils (Bekunda *et al.*, 2010; Smaling and Oenema, 2020). For the last 3 decades, inappropriate soil management practices have led to average losses of up to 660, 75 and 450 kg N, P and K ha<sup>-1</sup> (Smaling *et al.*, 1997), respectively, with 65% of cropland in Africa being degraded (Zingore *et al.*, 2015), resulting to annual nutrient loss worth US\$4 billion (Tekalign and Tegbaru, 2015). The poor agricultural practices have resulted in sub-optimal returns to investment, high food prices and overall food insecurity for smallholder households (Odera *et al.*, 2000; Omotayo *et al.*, 2022).

In Tanzania, maize (*Zea mays*) is a major economic driver, and a common staple crop cultivated by 80% of farmers (Minot, 2010; Chegere and Mrosso, 2022). Intensive research conducted on maize since 2002 has led to 1.5 Mt increment in attainable yields, above the previous production of 2.5 Mt (Rowhani, 2011). Integration of legumes in cereal systems has also been promoted to complement the dimly (<9% nationally) applied inorganic fertilizers (NBS, 2008; Kihara *et al.*, 2015a), improve soil fertility and buffer farmers from climate vulnerability (Chikowo *et al.*, 2020). Beans (*Phaseolus vulgaris*) and pigeon pea (*Cajanus cajan*) are important legumes mainly rotated and/or intercropped in maize-based systems and playing a key role in production, consumption, and income generation for the local farmers (Mligo *et al.*, 2001; Nchanji *et al.*, 2021).

Despite the 30-33% increment in per capita income, due to over emphasis in maize production research, the overall benefits of maize-legume systems are barely achieved (Amare *et al.*, 2012; Manda *et al.*, 2021). This can be attributed to the negative impact of maize on physiological development of intercropped legumes due to interspecific competition for light, moisture, and nutrients (Kimaro *et al.*, 2009; Masele *et al.*, 2022). The legume physiological alteration due to maize proliferation has resulted in 52% yield decline relative to that of legume monocrops (Ofori and Stern, 1987; Nassary *et al.*, 2020). Pigeon pea and bean yields have stagnated at 300 to 500 kg ha<sup>-1</sup>, though 1500 to 3000 kg ha<sup>-1</sup>, respectively, can be

potentially attained under proper management (Mligo and Craufurd, 2004; Hillocks *et al.*, 2006; Baijukya *et al.*, 2016). Interception of solar radiation by maize reduces radiation use efficiency by understorey legumes which compromises on biological nitrogen fixation (BNF) capacity and potential to produce nutrient-rich biomass for improving soil fertility (Woomer *et al.*, 2004). Farmers have resorted to cultivating bean monocrop systems within maize rotational phases as a coping strategy for the low bean yields (Mligo and Craufurd, 2004; Nassary *et al.*, 2020). However, bean monocrop systems are risk non-averse especially during the current period of unreliable weather (Mekuria and Waddington, 2002).

Development of cropping systems where the associated plant spatial patterns result in minimal competition would increase legume productivity without compromising maize yields (Kinyua *et al.*, 2023). During this study, cropping systems targeted on optimizing the exploitation of light, moisture, and nutrients for increased production of different intercropping components was introduced and their performance assessed. MBILI (Woomer *et al.*, 2004; Mongare *et al.*, 2021) and doubled-up legume (Chikowo *et al.*, 2020), are two innovative systems introduced and proven to be effective for improving legume yields in the increasingly reducing farmlands in Kenya and Malawi, respectively. Moreover, potential use of maize topping (Mashingaidze and Katsaruware, 2010; Rajkumara *et al.*, 2020), leaf stripping (Komarek *et al.*, 2021) and use of crop varieties with erectophile leaf architecture (Gitelson *et al.*, 2021) as strategies for reducing competition for growth resources in cereal-legume systems were examined.

Of critical importance is ensuring that introduction of improved cropping systems target to maintain rather than weaken the existing gender relations within farmer households (Moglia *et al.*, 2020). This is because some cropping systems like MBILI increases planting labor (Thuita *et al.*, 2011), which often result in women drudgery. In addition, low yielding crops like beans when intercropped in cereal-based systems, are often considered women crops and consumed at household level (Nakazi *et al.*, 2017). Contrary, male farmers exercise their control over crops associated with higher proceeds (Anderson *et al.*, 2021). Increased legume yield following successful manipulation of plant spatial patterns, under the improved cropping systems (Madembo *et al.*, 2020), might significantly affect the existing household dynamics. For example, improved bean production could increase its usability as commercial crop thus significantly influencing household decision making processes regarding use and control of the crop (Croson and Gneezy, 2009). Men might also dominate the sale of bean crop, which

is currently a women space (Nchanji *et al.*, 2021). Indeed, Njuki *et al.* (2011) documented a precedence where there is a shift to male producing legumes and control of associated incomes once they become cash crops. This could end up demotivating women once they fail to achieve food sufficiency for their households, despite providing required farm labor (Sulo *et al.*, 2012). Moreover, the shift in production and control of bean could have an impact on women and children who depend on the crop as a cheap source of protein (Snapp *et al.*, 2018). Unfulfilled expectations by one gender stratum, in favor of the other, may affect their perceptions regarding uptake of associated technology (Mudege *et al.*, 2018).

The existing agronomic innovation in a region affects the economic viability of farming operations being conducted (Adnan *et al.*, 2019). This explains why understanding farmer perceptions and behavioral changes after their exposure to improved cropping systems is critical in countering vices that may hinder uptake of the introduced technologies (Pathak *et al.*, 2019). This is because adoption involves major attitudinal components like technology acceptability, usability, and perceived economic benefits over the conventional systems (Haggblade *et al.*, 2004; Adnan *et al.*, 2019). Clare *et al.* (2014) indicated the need for a formal integration among the different socio-psychological, communication and innovation attributes in the adoption models being used to scale out introduced technologies. This informs on the need of creating awareness on how the introduced technology is designed and its associated performance (Nortje *et al.*, 2020). The achievement could be through creating proper channels that are accessible and in a form that farmers can easily decipher and apply (Mucheru-Muna *et al.*, 2021). On their end, researchers can aim at developing technologies that are socially and environmentally sound, that contributes to improvement of crop productivity as well as the sustainability of the agricultural enterprise (Ghadiyali and Kayasth, 2012).

Adoption of new technologies is influenced by farmer socio-economic characteristics and the size of land being utilized for crop production (Adrian *et al.*, 2005; Knowler and Bradshaw, 2007). Other critical factors include age of the farmer which is described to be inversely proportional to adoption of innovations (Macharia *et al.*, 2014) and resource endowment that directly relates to the rate and scale of adoption (Chavas and Nauges, 2020). In addition, farming experience and highest level of education reached by farmer is directly proportional to the rate of innovation adoption (Knowler and Bradshaw, 2007; Gao *et al.*, 2020). However, the influence of inherent characteristics of the introduced technology (such as technical

design) on its uptake by farmers ends up being neglected (Adnan *et al.*, 2019). For this reason, assessment of how the socio-economic factors within farmer households would affect their level of knowledge on implementing the introduced cropping systems was conducted. Moreover, the extent at which the innate characteristics of the introduced cropping systems influence gender driven decision making on the different field operational aspects by smallholder farmer households was examined.

## **1.2 Problem Statement and justification**

### **1.2.1 Problem statement**

Achieving food security status has been a major concern for majority of smallholder farming households whose production is characterized by a gradual, but consistent, degradation of croplands (Hutton *et al.*, 2017). Numerous research has been invested on improving maize production within intercropping systems (Minot, 2010; Kihara *et al.*, 2015a; Mugi-Ngenga *et al.*, 2022a) but with little attention on interspecific competition on intercropped legumes (Kimaro *et al.*, 2009; Sharma and Behera *et al.*, 2009). Studies on how integration of legumes in 2:1 intercrop system can increase maize production and amounts of N fixed have been conducted (Adu-Gyamfi *et al.*, 2007; Bekunda *et al.*, 2022). In Tanzania, yields of intercropped legume, such as pigeon pea, are still low ( $< 0.5 \text{ t ha}^{-1}$ ) despite a production potential  $> 1.5 \text{ t ha}^{-1}$  (Hillocks *et al.*, 2006). The biological nitrogen fixation capacity and systems' economics of the Malawian doubled-up legume (Mhango, 2011; Njira *et al.*, 2012; Mhango, 2017) and the Kenyan MBILI system (Mucheru-Muna *et al.*, 2010; 2011) with two legume species i.e., pigeon pea and beans, have not been tested in Tanzanian smallholder systems. Besides, improved legume yields following introduction of improved cropping systems may significantly influence household gender dynamics and decision-making processes regarding resource use and control (Huyer *et al.*, 2016). However, the extent which improved cropping systems affects household gender dynamics and the impact that changes in decision making may have on technology adoption by farmers is ill documented (Mudege *et al.*, 2018). Moreover, there is no clear understanding on how different socio-economic factors affect knowledge levels and technology uptake behavior (Macharia *et al.*, 2014).

### **1.2.2 Justification of the study**

With climate change and loss of soil fertility being evident in most smallholder farming systems of SSA, there is need of developing strategies to make farmer households more

resilient to such production shocks. One of the promising strategies is promoting crop diversification for improved yields, nutrition, incomes and soil health. Unfortunately, increased research focus and investment in the cereals has resulted in low yields of intercropped legumes. This creates a need for intentional research on improving legume production within intercrops, without compromising yields of the cereal maincrop. This study examined how promising cropping systems can be tailored to suit farming systems of Babati, Tanzania with an aim of improving soil fertility, and production economics. In addition, the impact that introduction of such novel innovations would have on household gender dynamics and farmer knowledge levels warranted assessment.

### **1.3 Research Questions**

This study sought to answer the following questions:

- i. How are farm economics affected by introduction of improved cropping systems in Gallapo, Sabilo and Riroda villages of Babati?
- ii. To what extent do different cropping systems affect the biological nitrogen fixation of intercropped legumes?
- iii. What impact does different cropping systems have on crop physiological properties and soil physical-chemical characteristics?
- iv. How does gender of farmer influence agricultural-based decisions regarding implementation of improved cropping systems in Gallapo, Sabilo and Riroda villages of Babati?
- v. How do different socio-economic factors influence farmer knowledge on implementing improved cropping systems?

## **1.4 Research Objectives**

The objectives of the study were:

- i. To assess the agronomic and economic gains of improved cropping systems in Gallapo, Sabilo and Riroda villages of Babati
- ii. To examine the effect of different cropping systems on biological nitrogen fixation capacity of intercropped legumes
- iii. To evaluate how different cropping systems, influence crop physiological characteristics and physical-chemical properties of soil in Gallapo, Sabilo and Riroda villages of Babati
- iv. To assess the influence of farmer gender on agricultural-based decisions making process on implementation of improved cropping systems in Gallapo, Sabilo and Riroda villages of Babati
- v. To examine how different socio-economic factors affect farmer knowledge on implementing improved cropping systems.

## **1.5 Hypotheses**

The study was guided by the following hypotheses:

- i. Improved cropping systems can not increase the economics of conventional cereal-legume intercropping systems
- ii. Cropping systems do not influence biological nitrogen fixation of intercropped legumes
- iii. Crop physiological characteristics and physical-chemical properties of soil are not influenced by different cropping systems and agro-ecological conditions
- iv. The gender of farmer does not influence agricultural decisions on implementing improved cropping systems
- v. Different socio-economic factors such as gender, age and household income do not influence farmer knowledge on implementing improved cropping systems.

## **1.6 Significance of Study**

The assessment of different plant spatial patterns under maize-legume intercropping is important for providing farmers with more intercropping systems' options that can help to improve soil fertility, increase legume yields, household incomes and food security. The study will also help policy makers, general agricultural practitioners, and stakeholders to appreciate the value of improving legume productivity in realizing optimal benefits from biological nitrogen fixation to reduce farmer expenses on inorganic fertilizers. The findings will help researchers in narrowing the basket of options on promising cereal-legume intercropping systems that may require further suitability studies to different agro-ecological conditions. Besides, researchers and scholars will increase their understanding on the impact of introducing improved agricultural technologies on gender relations and farmer knowledge at household level.

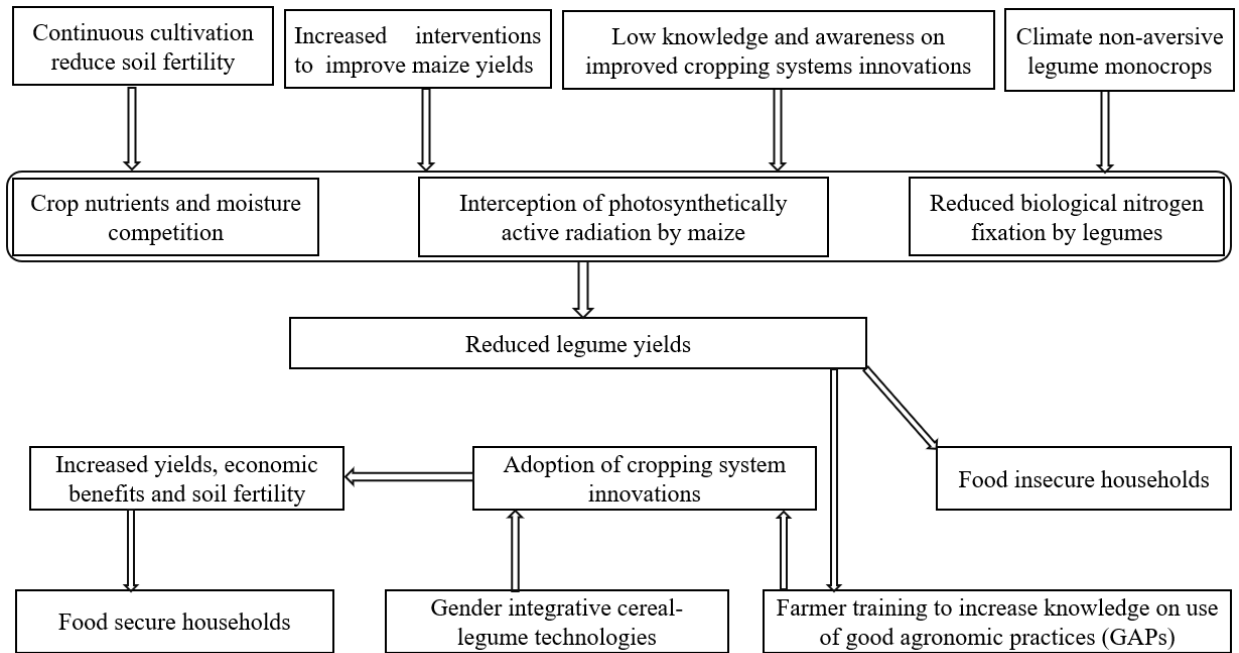
## **1.7 Scope of study**

This study addresses the challenge of vulnerability of conventional 1:1 and 2:1 cropping systems to changing climate through crop diversification. Strategies for increasing legume productivity under maize-based systems of Babati District of northern Tanzania are explored. These strategies include manipulation of plant spatial configurations of promising cropping systems that have been tested and proved to be economically beneficial and climate smart,

and exploration of varieties and species with phenological traits that improve light penetration to intercropped legumes, without compromising yields of the cereal main crop. Field assessments were conducted at farm level, with cropping systems as treatments, while socio-economic characteristics, knowledge, attitude, and perceptions of farmers towards technologies under test were examined at both household and community level.

## **1.8 Conceptual Framework**

Using inappropriate agronomic approaches to feed the growing population and increased dependency on already strained resources has led to food insecure households (Belay, 2014). This has led to over-cultivation of land which has degraded the finite arable lands (Bekunda *et al.*, 2010). Over emphasizing maize production research has led to increased maize yields (Minot, 2010) but negatively impacted on yields of intercropped legumes (Kimaro *et al.*, 2009). Besides, farmers have limited knowledge on agricultural adaptation and resilience resulting in cultivation of climate non-averse legume monocrops (Mligo and Craufurd, 2004). Increasing farmer knowledge through training on good agronomic practices in crop production can increase legume yields by limiting interspecific competition amongst companion crops (Madembo *et al.*, 2020). Moreover, embracing gender integrative agronomic research approaches during implementation of new technologies can avoid introduction of gender related constraints that may limit technology uptake by farmers (Wegulo *et al.*, 2009; Nchanji *et al.*, 2021) as indicated in Figure 1.1.



*Figure 1.1 Conceptual framework indicating factors affecting legume production in cereal-based intercropping system in Babati District of Northern Tanzania*

## 1.9 Definition of Terms

<b>Agro-ecological zone</b>	Land-use planning used to separate areas based on soil, landforms, and climatic conditions
<b>Cropping system</b>	A specific way in which crops are organized and managed while considering their spatio-temporal aspect within a plot of land
<b>Doubled-up legume system</b>	Intercropping two grain legumes to exploit their complementing growth habits and structural architecture
<b>Erectophiled plants</b>	Plant with vertical leaf architecture
<b>Farmer practice</b>	A cropping system where maize and pigeonpea are intercropped, with sowing done behind tractor/animal drawn plough and dismal or no fertilizer application
<b>MBILI</b>	A cropping system where double maize rows are alternated with two rows of a single legume species
<b>Mbili - Mbili</b>	A cropping system where double rows of maize are alternated with two legume species
<b>Planophiled plants</b>	Plants with horizontal leaf architecture
<b>Topping</b>	Nipping maize leaves 10 cm above the ear leaf at physiological maturity
<b>Stripping</b>	Removal of four lower maize leaves at a period between tasselling and silking

## CHAPTER TWO: LITERATURE REVIEW

### 2.1 Overview

In sub-Saharan Africa (SSA), agricultural production is characterized by crop nutrient mining which has led to degradation of farmlands (Bekunda *et al.*, 2010; Ten Berge *et al.*, 2019). The problem emanates from inappropriate field management practices, extreme weather, and limited access to agricultural production resources by farmers (Zingore *et al.*, 2007). Nutrient mining demands by cereal crops i.e., 20 - 50 kg N ha<sup>-1</sup>, and 3 - 10 kg N ha<sup>-1</sup> eroded through runoff and grain and biomass removal, respectively, far out-weighs the 5 - 10 kg N ha<sup>-1</sup> nutrient replenishment rates by legumes (Brekke *et al.*, 1999; Bobbink *et al.*, 2010). This has resulted in escalated food insecurity with the greater population unable to meet their daily dietary requirements (Bjornlund *et al.*, 2022).

Cereal-legume rotations and intercropping have been promoted due to the complementary nature of the two crops (Kimaro *et al.*, 2009; Duchene *et al.*, 2017). Besides the provision of protein rich nutrition, soil cover and reducing soil nutrient losses, legumes like pigeon peas stimulate BNF which replenishes soil N for use by the subsequent maize crop (Adu-Gyamfi, *et al.*, 2007; Kafeel *et al.*, 2023). However, yields of intercropped legumes are often low due to shading by the maize main crop (Masele *et al.*, 2022).

Decline in soil fertility is one of the yield limiting factors in majority of smallholder farming systems of SSA (Kihara *et al.*, 2017). This challenge becomes more pronounced following the increase in seasonal weather variability in a region that is highly dependent of rainfed agriculture (Kisaka *et al.*, 2016). To overcome these challenges, there is need of transforming the existing cropping systems by making them more resilient to changing weather and sustainable to preserve the integrity of the immediate environment (Kizito *et al.*, 2022). Adoption of ISFM practices has a great potential for improving crop yields while ensuring that the long-term productivity i.e., sustainability, of the soil is not compromised (Vanlauwe and Dobermann, 2020). While this works for some category of farmers, especially the resource endowed, it faces challenge of adoption by farmers with limited resources resulting in dwindling of crop yields (Tey *et al.*, 2014). The volatile prices of fertilizer inputs make them inaccessible by resource poor farmers (Snapp *et al.*, 2023). The same farmers may also face limitations of accessing organic manure because they keep few or no livestock while they

sell crop residues after harvest to supplement the income from grain sales (Chia *et al.*, 2019; Härri *et al.*, 2020; Mgozoli *et al.*, 2020). For resource endowed farmers, use of fertilizers is targeted on maize resulting in ‘maize bloom’ (Ooro *et al.*, 2023). Proliferation of maize results in interspecific competition for nutrients, moisture, and shade with the understorey legume (Kimaro *et al.*, 2009). This has resulted in the reportedly low legume yields in maize-legume systems that hinder optimization of crop production benefits by farmers (Kinyua *et al.*, 2023). There is a need to improve the existing cropping systems to ensure increased production of legumes without compromising on maize yields (Madembo *et al.*, 2020). This will increase benefits through optimized yields of the intercropping component, improve soil fertility through BNF and reduce vulnerability to climate associated risks (Lin, 2011).

Exploration on how plant spatial patterns and phenological traits can be manipulated to allow improved productivity of the legume component while maintaining the population and production of the cereal companion has great potential to unlock economic benefits of intercropping systems (Kinyua *et al.*, 2023). This may require adopting the existing improved systems such as MBILI (Mucheru-Muna *et al.*, 2010) and doubled-up legume rotation (Chikowo *et al.*, 2020) that have been developed to meet the same goal or tailoring these technologies into innovations contextualized to meet the crop production needs of the specific farmers. However, successful introduction and adoption of new technologies may require involvement of farmers from the design, testing and scaling stages (Kernecker *et al.*, 2021). This is because farmers adopt technologies which they perceive to be consistent with their existing systems and borrows from learnings of the past experiences which has potential to meet their crop production needs (Adnan *et al.*, 2019). This means that for the introduced innovations to be accepted, they must be well grounded on farmers’ attitudinal acceptance levels (Maertens *et al.*, 2021). For example, farmers consider innovations and their compatibility to the local conditions as one and the same thing (Sattler and Nagel, 2010). In addition, farmers avoid testing technologies that have low likelihood of adoption (Maertens *et al.*, 2021). Indeed, Aubert *et al.* (2012) indicated that trialability of innovations by farmers is a strong predictor of their adoption.

Despite the success of designing, testing and rollout of new technologies for scaling by farmers, their effects on household gender dynamics relating to decision making and how

these dynamics affect uptake of introduced technologies need close examination. This is because introduction of an innovation may have both positive and/or negative impact on different members of farmer households (McGuire *et al.*, 2022). In addition, farmers of different gender stratum show willingness to adapt technologies that meet specific production needs which vary across different members of the same household (Galiè *et al.*, 2022). Indeed, introduction of new innovations results in changes in agricultural production which can be resisted by some household members (Gyau *et al.*, 2014). This might be caused by a wrong perception, lack of proper information (Ayalew *et al.*, 2022) and required resources to implement or inadequate facilitation on effective use the innovation (Tey *et al.*, 2014). For this reason, introduction of agronomic interventions should be well facilitated and targeted at maintaining or improving (rather than collapsing) the existing household gender relations, roles, and status (Ayalew *et al.*, 2022; Ryan, 2022).

Communication and training during the scaling of agronomic innovations is an essential ingredient for their adoption by farmers (Ayalew *et al.*, 2022). The two aspects have important contribution to increasing farmers' understanding and knowledge of the innovations (McGuire *et al.*, 2022). With proper communication, farmers can weigh the attributes on the innovation and decide whether they will implement the technology in its original state or adapt before adoption (Clarkson *et al.*, 2022). Prokopy *et al.* (2015) documented the role of social learning and influence, and peer pressure in shaping decision to adopt or evaluate attributes of an innovation. Moreover, different socio-economic factors such as gender, age and involvement in other income generating activities affect farmer knowledge on implementation of introduced technologies (Macharia *et al.*, 2014). Understanding the above-mentioned factors can help to inform farmers' capacity to scale out the introduced technologies.

## **2.2 Existing Cropping System Innovations and their Influence on Agricultural Profitability**

Maize is an important staple crop for majority of smallholder farming households in SSA (Santpoort, 2020). The crop is cultivated in more than 33 million hectares of land in SSA (Blackie and Jones, 1993; Macauley and Ramadjita, 2015). On average, maize yields on smallholder farmer fields is as low as 1 t ha<sup>-1</sup> (Myaka *et al.*, 2006; Vesterager *et al.*, 2008). The major contributor of low maize yield is reducing or inherently low soil fertility (Smaling

*et al.*, 2015), unreliable weather with increasing frequency in occurrence of drought and dry spells (Kisaka *et al.*, 2016) and soil erosion (Pimentel and Burgess, 2013). The above edaphic factors are compounded by inadequate use of good management practices such as continuous cultivation of land with reduced or failure to apply nutrient inputs (Smaling *et al.*, 2015; Ezui *et al.*, 2022). For example, fertilizer application across crop fields in SSA were previously reported to be at an average of 9 kg ha<sup>-1</sup> by Crawford *et al.* (2006) with adoption rates of as low as 3% (Kihara *et al.*, 2015a) and later at 20 kg ha<sup>-1</sup>yr<sup>-1</sup> by Vanlauwe and Doberman (2020) but with negative nutrient balances of -22, -2.5 and -15 kg ha<sup>-1</sup> yr<sup>-1</sup> of NPK, respectively, (Smaling *et al.*, 2015). This means that at least 22 kg of N fertilizer is required in smallholder fields to overcome the challenge of nutrient mining (Ezui *et al.*, 2022).

Regeneration of soil fertility in SSA farmlands has for a long time revolved around practicing bush fallows, a trend that has diminished following fragmentation of the limited arable lands (Partey *et al.*, 2017). Measures aimed at promoting soil fertility increase with little investment in financial resources have been encouraged to help unlock crop productivity in smallholder systems (Mdlambuzi *et al.*, 2022). Amongst the many strategies promoted is cereal-legume intercropping/rotations for improving soil fertility and increasing climate resilience of smallholder farmer livelihoods (Mugi-Ngenga *et al.*, 2022a; Madembo *et al.*, 2020). The outcome of cereal-legume integration in farmer systems has been 61% increase (Waddington *et al.*, 2007) to doubling of grain yield relative to production under continuous sole systems (Vesterager *et al.*, 2008). A further integration of mineral fertilizers in cereal-legume systems has yielded tremendous production gains (Kihara *et al.*, 2021). Waddington *et al.* (2007) reporting 29% extra grain production per maize plant under pigeon pea intercropping relative to single plants cultivated in a sole maize system, and after both received fertilizer application.

Cereal-legume integration does not only benefit farmer through enhanced nutrition and increased yields but also soil organisms through below ground interactions (Brussaard *et al.*, 2007; Duchene *et al.*, 2017). Intercropping systems supports development of different root types due to diversified root architecture and distribution besides generating exudates that are source of energy for microbial communities in the soil (Bargaz *et al.*, 2015). Indeed, Tang *et al.* (2014) documented improved microbial biomass and activity, such as colonization by plant growth-promoting rhizobia, in systems where legumes are integrated as intercrops. This

increases efficiency of some functional microbes such as nitrogen fixing rhizobia and mycorrhiza fungi that injects inaccessible nutrients and phytohormones that promotes growth of plants and development of root architecture (Bolo *et al.*, 2021). Fresh materials from abscised biomass from legumes also increase decomposition of SOM which also stimulate the activity of microbes involved in mineralization of stable soil organic matter (Cheng, 2009).

Agroforestry practices using nutrient-rich trees like *Gliricidia* which produces up to 13 t ha<sup>-1</sup> of biomass have also been reported (Akinnifesi *et al.*, 2007) to improve maize yield by 61% (Chirwa *et al.*, 2003) while enhancing nitrogen agronomic efficiency. Utilization of green manure cover crops such as mucuna with some level of fertilization as a strategy of boosting maize yields has been a success (Mucheru-Muna *et al.*, 2014). Adjei-Nsiah *et al.* (2007) reported increased grain yield following integration of green manure cover crops, however, labour requirement for managing the legume has been a disincentive for adoption of the technology by farmers (Douthwaite *et al.*, 2002).

Conservation agriculture involving reduced soil disturbance through minimum tillage, some level of soil cover through retention of residue mulch or cover cropping and crop diversification by intercropping and rotations has been promoted as another solution designed for unlocking the low crop yields (Kinyua *et al.*, 2021; Mgozeli *et al.*, 2020). This system is associated with improved soil health because it promotes diversity and activities of soil fauna, enhance rainwater infiltration, reduces soil erosion, regulates soil temperature, and improves soil structure (Bolo *et al.*, 2023). Studies on conservation agriculture have however reported controversial results. For example, Thierfelder *et al.* (2013) reported increases in maize grain yield, Kihara *et al.* (2011a) documented yield decline and Kinyua *et al.* (2021) indicated similar yields relative to conventionally tilled systems. This is an indication that the system is suitable for specific agro-ecological conditions as reported by Michler *et al.* (2019).

In the last decades, adjustment of plant spatial configurations aimed at reducing interspecific competition among intercropped components has been targeted to address the productivity of legumes without compromising yields of the cereal component (Woomer *et al.*, 2004; Begam *et al.*, 2020). Sub-optimal production of Moja (Swahili word for one; Banik, 1996) intercropping has been overcome by introducing new intercropping systems dubbed MBILI (an abbreviation for ‘Managing Beneficial Interactions in Legume Intercrops’). MBILI system

was introduced, in Kenya, tested and proven to be profitable and climate averse (Woomer *et al.*, 2004; Mucheru-Muna *et al.*, 2011). The system performs well in soils of varying fertility gradients hence superior to Moja intercropping (Mucheru-Muna *et al.*, 2010).

The most interesting aspect of MBILI system is its ability to reduced interspecific competition reported under intercropping systems by allowing complementarity of companion crops (Begam *et al.*, 2020). By exploiting plant spatial patterns and complementarity of intercropping components in MBILI, the system allows 54% penetration of photosynthetically active radiation (PAR) to understorey legumes (Mucheru-Muna *et al.*, 2011; Clark, 2019) which improves their productivity. Studies have reported a 1.7 t ha<sup>-1</sup> increase in maize (Ngetich *et al.*, 2014) and 250 kg ha<sup>-1</sup> in bean yields under MBILI (Thuita *et al.*, 2011) making it more economically viable due to higher land equivalent ratio than Moja intercropping. Improved growth of legumes has also been documented as offering a facilitative interaction between plants and roots which helps in averting environmental stress thus enhancing crop yields (Dowling *et al.*, 2021). Integration of deep-rooted crops like pigeon pea in intercropped systems helps in mobilizing both the limited and/or unavailable nutrients, like phosphorus, making them accessible for use by shallow rooted crops (Kimaro *et al.*, 2009).

In Malawi, doubled-up legume system was developed to help in optimizing the production potential of grain legumes (Mhango *et al.*, 2017). The system has a potential of “doubling” soil fertility and economic proceeds from two species of pulses relative to pure legume stands (Chikowo *et al.*, 2020). In addition, it provides improved protein nutrition, food diversity and saves on operational labor (Phiri *et al.*, 2012). The abscised leaves can increase yields of subsequent maize crop by up to 640 kg ha<sup>-1</sup> relative to Moja intercrop and 1 t ha<sup>-1</sup> higher than maize monocrop (Snapp *et al.*, 2002). Furthermore, the subsequent maize rotation requires 50% of recommended inorganic N amount to produce yields comparable to full fertilization making the system economical for resource poor households (Chikowo *et al.*, 2020). This validates the principle on legumes providing a critical pathway for amplifying benefits accrued from utilizing the dismal fertilizer amounts by majority of farmers in Africa (Yakubu *et al.*, 2010a).

Cropping system manipulations such as maize topping eliminates “tassel shading” and apical dominance effect (Subedi, 1995) while promoting improved interception, nutrient uptake, and photosynthetic efficacy (Rathika, 2013) for slow growing understorey legumes like pigeon

pea. Mashingaidze and Katsaruware (2010) reported a 5.46% increase in grain yield, 11.7% in 1000 grain weight, 11% in grains per pods and 17% in pods per cowpea plant after topping maize besides improved grain quality and marketability. This is because dry matter production by understorey intercrops is relative to the intensity companion crops intercept solar radiation (Koester *et al.*, 2014). Maize tassel intercepts between 2-40% of solar radiation (at 8 - 15 plants/m<sup>2</sup>) while the canopy intercepts 40% of solar radiation (at 2 plants/m<sup>2</sup>) from 35 days after planting hence only 60% of light reach intercropped plants at this stage, even lesser at later stages (Tetio-Kagho and Gardner, 1988). Increasing light interception, without compromising the production of cereal crop, can therefore promote proliferation of understorey legumes thus optimizing economic benefits derived from a cropping system (Myaka *et al.*, 2006; Kimaro *et al.*, 2009).

### **2.3 Effect of Cereal-Legume Cropping Systems on Biological Nitrogen Fixation**

Legumes are important component of smallholder farming systems because of the role they play as source of nutrient-rich food that is affordable to majority of resource poor farmers (Drewnowski, 2010). Besides their role in promoting food security, legume crops are key in soil fertility replenishment (Lan *et al.*, 2023). This benefit is achieved through fixation of atmospheric derived N (Matusso *et al.*, 2014) which provides up to 80% of their nutrient demands (Wani *et al.*, 1995). In addition, their benefits to subsequent (cereal) crops and soil living organisms are achieved when their residues are retained in the field after plant harvest (Peoples *et al.*, 2021). The soil fertility replenishment capability of legumes is enhanced by root nodules which act as sites for colonization by nitrogen fixing microbes e.g., rhizobia, azolla, bradyrhizobia among others (Nyoki and Ndakidemi, 2016; Bolo *et al.*, 2021). The sustainability of utilizing legumes as enhancers of soil fertility can be attributed to their efficiency in N release with lower greenhouse footprint than mineral fertilizers (Sa *et al.*, 2013). This makes legumes good alternative for improving soil fertility and crop yields in areas characterized by limited utilization of mineral fertilizers (Sheahan and Barrett, 2017).

Despite acting as a remedy for replenishing soil N, the amount of N fixed vary among the different legume species (Peoples *et al.*, 2021). For example, Mhango (2011) reported nitrogen fixation by pigeon pea - groundnuts intercrop to be between 42-83 kg N ha<sup>-1</sup> while Njira *et al.* (2012) reported 53.6 kg N ha<sup>-1</sup> from a pigeon pea-soybean system. Elsewhere,

Njira *et al.* (2017) reported 92.9 kg N ha<sup>-1</sup> from sole pigeon pea system, 62.5 kg N ha<sup>-1</sup> from sole cowpea and 59.9 kg N ha<sup>-1</sup> from pigeon pea-maize system. In addition to N fixation variability across different legume genotypes, some species such as common beans are known to have a dismal contribution to soil fertility replenishment (Peoples *et al.*, 2009). However, Vanlauwe *et al.* (2019) attributed the sub-optimal fixation yield to less focus on optimizing the potential of nitrogen fixation genes by bean breeders. Optimizing the nitrogen fixation yield by legume-based cropping systems can be of great help in harnessing their nutrient replenishing capacity (Abubakari *et al.*, 2016). This can benefit resource poor farmers by preventing nutrient mining while saving on the high fertilizer expenses (Chikowo *et al.*, 2020).

The environment where legumes are cultivated plays a key role in improving soil fertility through nitrogen fixation (Chikowo *et al.*, 2020). Low fixation rates have been reported in seasons characterized by moisture I (Torabian *et al.*, 2019). In addition, biophysical factors such as the amounts of available nutrients i.e., N, P and Mo can affect the N fixation levels of legumes (Weisany *et al.*, 2013). Soils high in mineral N levels are known to have poor fixation of atmospheric N (Peoples *et al.*, 2009). This is because legumes cultivated in such soil have abundant N reserve required for growth hence do not need to fix extra N (Cardoso *et al.*, 2007). On the other hand, deficiencies of P and Mo are known to negatively impact on the ability of legumes to fix nitrogen derived from atmosphere (Didagbe *et al.*, 2014). Phosphorus is required for root development, which harbors nodules that are powerhouse for nitrogen fixing bacteria, a substrate for photosynthesis and promotes translocation of sugars (Hardarson and Atkins, 2003). In addition, the activity of nitrogen fixing bacteria is affected by soil pH with low levels denaturing their activity (Bolo *et al.*, 2021).

The component crops within a cropping system have a stake on productivity of legumes during nitrogen fixation (Mogale *et al.*, 2023). Integration of legume and cereals within a cropping system helps to optimize the nitrogen fixation process by legumes (Mugi-Ngenga *et al.*, 2022b). This is because maize is a heavy feeder of nutrients and with potential of over exploitation of nitrogen in nutrient limited soils (Sanginga and Woomer, 2009). Limitation of N in the soil stimulates a consecutive fixation of atmospheric N by the intercropped legumes which replenishes what was taken up by cereal crops (Cardoso *et al.*, 2007). Chikowo *et al.* (2020) reported an increased fixation rate of N derived from atmosphere under doubled-up

legume rotation where two species of legumes with a complimentary growth habit are strip cropped. The higher fixed N yield in pure legume systems such as doubled-up legume rotation than cereal-legume rotation was attributed to the greater biomass yield of the former than the later (Franke *et al.*, 2018; Kermah *et al.*, 2018).

To reap maximum benefits from N derived from atmosphere, farmers are advised to practice crop residue retention after crop harvests (Hu *et al.*, 2021). This is because significant amounts of N are removed from crop fields when residues from legumes are exported for off-field feeding of livestock (Congreves *et al.*, 2021). Despite the possibility of recovering some nutrients back to the fields through application of farmyard manure (developed from composting residual organic matter from animal shed and animal excreta), much of the manure does not reach fields located away from homestead (Njoroge *et al.*, 2019; Namatsheve *et al.*, 2021). Ideally, it is the fields located near the homestead that benefits from nutrient translocation (Fanjaniaina *et al.*, 2021). The labor needed to transport manure and other organic materials back to the out-fields acts as a major disincentive to majority of smallholder farmers (Cholo *et al.*, 2020). However, farmers still benefit from fallen leaf biomass and residual roots even after above ground biomass is removed from crop fields (Mugi-Ngenga *et al.*, 2022a). Interestingly, Ncube *et al.* (2009) indicated nutrient derived from decomposition of fallen leaves to be more than that of removed legume residues while Peoples *et al.* (2009) established that a third of N-fixed by legumes remains in the soil.

#### **2.4 Influence of Soil Bio-geochemical Properties and Plant Phenological Traits on Crop Production**

Soil plays an important role in crop production being the medium for anchorage and source of nutrients for facilitating growth (Ortiz and Sansinenea, 2022). The biophysical conditions of soil can determine its health and productivity of crops being cultivated (Tchuwa *et al.*, 2022). For example, the ability of legume crops to biologically fix atmospheric nitrogen is determined by soil pH and calcium deficiencies which inhibit nodulation process (Kafeel *et al.*, 2023). The amount and availability of molybdenum and cobalt, which are essential nutrients for enhancing nodulation, is also affected by low soil pH (Abubakari *et al.*, 2016). Phosphorus is another critical nutrient for root development, but low soil pH causes fixation of the nutrient into insoluble and unavailable forms (Lemos *et al.*, 2022). Unavailability of P

nutrient also limits uptake of other nutrients such as N (Kinyua *et al.*, 2021). This is because short and deteriorated plant roots have inefficient uptake of important growth nutrients (Sulieman and Hago, 2009). Liming of soil allows  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  to displace the  $\text{Al}^{2+}$ ,  $\text{H}^+$ ,  $\text{Cu}^{2+}$ ,  $\text{Fe}^{2+}$  and  $\text{Mn}^{4+}$  from the adsorption sites of the soil thus improving the pH level (Abubakari *et al.*, 2016). On the contrary, high levels of soil N reduces biological nitrogen fixation potential of legume crops (Laws and Graves, 2005). In such scenarios, legumes luxuriously access sufficient N to support their growth which inhibits nodule development (Taylor *et al.*, 2005). Unfortunately, high levels of N in the soil coupled by successive application of N fertilizer does not result in a consecutive use efficiency and yield increase but promotes development of a leafy biomass (He *et al.*, 2022). In addition, it is detrimental to the environment since only a small portion of the fertilizer is utilized by plants (Kinyua *et al.*, 2021; Amarasinghe *et al.*, 2022). Considering that fertilizers are expensive sources of plant nutrients and are unaffordable to farmers with low resource endowment, alternative plant nutrient options are necessary to complement its use (Mdlambuzi *et al.*, 2022).

Rhizobium inoculants have been promoted as cheaper, more efficient, and environmental friendlier strategy for improving legume yields compared to fertilizers (Abubakari *et al.*, 2016). These inoculants are effective particularly for agricultural fields where N deficiency is the dominant crop yield limiting factor (Abdullahi *et al.*, 2022). Use of Rhizobium inoculant has been reported to increase the amount of N fixed by legumes by up to 46% thus further reducing on the fertilizer requirement for subsequent cereal crop (Yakubu *et al.*, 2010b). Unfortunately, farmers have limited knowledge on use and access of rhizobium inoculants (Kiwia *et al.*, 2022). This invokes the need for increased sensitization on inoculant use (Mohammed and Abdulai, 2022) and/or promotion of alternative locally available sources of nutrient for consistently degrading smallholder systems.

Manure application is a good soil fertility improvement strategy for smallholder farming systems (Onwonga *et al.*, 2008). Studies have reported on positive influence of manure on maintaining sustainable production of agricultural soils (Tchuwa *et al.*, 2022). This includes increased mineralization of N and P nutrients because of enhanced activity of solubilizer strains of microbes (Sulieman and Hago, 2009). Micronutrients such as Zn and B have been reported to significantly increase in manure applied systems (Ferreira *et al.*, 2022; Reimer *et*

*al.*, 2023). In addition, increased frequency in application improves soil structure which enhances soil water infiltration and retention while moderating soil pH (Fu *et al.*, 2022). This is beneficial to farmers of low resource endowment, who cannot afford agricultural lime for their acidic soils (Ano and Ubochi, 2007).

Despite the benefits derived from utilizing manure, average use (~60%) of this resource has been reported in smallholder systems (Kihara *et al.*, 2015a; Mponela *et al.*, 2023). This can be associated with the high labor requirements in preparation, transportation, and application (Geta *et al.*, 2013; Cholo *et al.*, 2020). In addition, reducing land holdings due to land fragmentation has accelerated shortage of pastures and forage, thus limiting livestock production (Chiaka and Zhen, 2021). For majority of farmers who use manure, its application is usually haphazard with low quantities, reduced frequencies and under through poor soil application methods (Kome *et al.*, (2018). For sustainability of crop production, it is important for farmers to combine application of manure with judicious use of site-specific fertilizer recommendations so that the available quantities can cover larger portions of crop land (Tchuwa *et al.*, 2022). Integration of manure and fertilizers can be accompanied by GAPs to ensure that economically feasible amounts of nutrient resources are applied and consecutively utilized by crops, with minimal losses to the environment (Vanlauwe *et al.*, 2015).

Good agronomic practices encompass understanding what the suitable crop varieties and combinations to plant are (Sime and Aune, 2018). Use of climate information services can help to guide on suitable choice of crop varieties (Kihara *et al.*, 2021) while the selected crop combinations dictate plant spatial configurations to be used by farmers (Madembo *et al.*, 2020). While efficient utilization of fertilizers should be guided by the 4R-fertilizer stewardship i.e., right source, rates, time, and placement (He *et al.*, 2022), poor spacing may result in interspecific competition or wastage of applied nutrients affecting attainable yields (Kimaro *et al.*, 2009). In addition, proper spacing promotes maximum interception of light with minimal competition among the intercropping components (Clark, 2019; Kinyua *et al.*, 2023). The existence of unhealthy competition among intercropping components can be identified through plant chlorophyll density, which is a proxy of the amount of N available in the soil for plant uptake (Xiong *et al.*, 2015). Crop growth is also retarded while development of branches and production of flowers in legumes can be linked to increased shading by the

cereal companion (Angadi *et al.*, 2022). Ability to conduct visual diagnostic of crops can guide the farmer on the required agronomic management practices which can help in averting the associated yield losses (Ichami *et al.*, 2022).

## **2.5 Influence of Gender on Agricultural-Based Decision-Making**

Gender assessment encompass seeking information about male and female farmers to understand their roles, responsibilities, access, and control of resources as well as unveiling hidden power structures which shape the relationships between them (UNDP, 2010). Puskur (2013) reported that “failure to recognize their roles, differences and inequalities poses threat to the effectiveness of agricultural development”. Little is documented about the relationship between ownership of farmland and the gender of household members who solely or jointly decides and/or implements field activities because the required data on these variables is limited (Twyman *et al.*, 2015).

Ensuring gender equity and inclusion during the development of agricultural technologies is critical for success in adoption of the recommended innovations (Meinzen-Dick *et al.*, 2014; McGuire *et al.*, 2022). This is because of differences in preferences, choices, power over resource use and control and exposure to different constraints vary across gender (Ragasa *et al.*, 2013). Often, women have limited power in asset ownership, reduced capital, education, and technical information access compared to men (Peterman *et al.*, 2014). In most agricultural systems, women are the major source of subsistence-based farming labor (Baudron *et al.*, 2019). This is besides their responsibility for family food production, while men mainly engage in market-oriented production (Amugsi *et al.*, 2016; Weltzien *et al.*, 2019). Women engaged in produce markets are also expected to provide labor for other household chores including sourcing and preparing meals (Medagbe *et al.*, 2020). This makes women to have preferences on certain species of crops and vegetables needed to meet their household food requirements, despite having constraint in resources for investing in farming (Smith and Chavas, 2007). In Malawi, Quisumbing and Pandolfelli (2010) reported reduced purchase of seed and fertilizer by women because the size of packages was bigger than they could afford. Limited power over access and control of land also contributes to their inability to influence decisions regarding use of family resources (Peterman *et al.*, 2011).

Due to many years of farming experience and provision of labor, women in some communities are slowly gaining power on decision making involving some farming aspects (Shibata *et al.*, 2020). In Sierra Leone, Richards (1986) documented how farmers consult women on decision and supervision relating to sorting of planting materials to be used in the successive season. Despite emerging instances of women involvement in decision making, they are rarely involved in decision relating to control of income generated (Shibata *et al.*, 2020). This is despite their critical role in labor provision. In some communities, their labor contribution may be greater than that of men (Tipilda *et al.*, 2008).

Adoption of new technologies is not an instant process but a decision-making process that takes time since farmers try an innovation and then decide whether to scale it (Martínez-García *et al.*, 2013). Technology adoption needs to go hand in hand with gender targeted empowerment so that all farmers irrespective of their gender make own decisions to adopt instead of adopting recommendations made by others (Bartlett, 2005). To ensure introduced agricultural innovations are comfortably taken up, there is need of understanding the role of gender in allocating responsibilities and defining who ultimately reaps the largest share of resulting benefits (Elias *et al.*, 2017). This is because men and women have different reasons for adopting a technology, since they reap variable benefits (Sulo *et al.*, 2012). Some technologies are easily adopted by specific gender compared to the other despite the set of technologies being packaged and scaled in a similar manner (Hallman *et al.*, 2007). Technology preferences within gender is a factor of emphasis and value men and women attach to it (Bellon *et al.*, 2006). In addition, the cost and benefits accrued from a system could trigger risk averseness, which varies between male and female farmers (Croson and Gneezy, 2009).

Participatory action research has shown some potential in reducing gender alienation in decision making process, empowering women for conflict resolution and increasing their frequency in negotiations with policy makers (Colfer, 2005). The process could start with ensuring involvement of women, starting with gender balance amongst agricultural scientist to raise their voice during agricultural-based policy making (Akeredolu, 2008; Beintema and Di Marcantonio, 2010). This would result in empowered women with influence on policies and decisions. Besides, policies and measures that need to be put in place to optimize

technology adoption with reduced negative implications on gender should be established (Tsige *et al.*, 2020).

## **2.6 Acquisition of Farmer Knowledge on Uptake of Innovative Technologies**

According to experiential learning theory, learning occurs when knowledge is created through experiences (Kolb *et al.*, 2001). In an agricultural context, farmers learn after they are exposed to some concrete experience such as agronomic innovations that they experiment over time (Tchuwa *et al.*, 2022). Through the process of experimentation, participant farmers make observations and interact with innovations resulting in creation of abstract concepts on how to adapt the knowledge gained to their local context (Koob *et al.*, 2002). The experimentation - adaptation process results in adoption of new technologies after which a new learning cycle begins. Experiential learning theory is different from transformational learning theory where farmers are required to listen, decipher, and implement knowledge disseminated by trainers (Boström *et al.*, 2018). This form of learning aims at giving farmers freedom to think and offer solutions to their crop production challenges rather than reproducing solutions that are developed and disseminated by researchers (Rodela, 2011). Social learning theory contrasts the previously mentioned theories since farmers learn through cross fertilization of knowledge from their colleagues, farmer groups and community at large (Mapiye *et al.*, 2006). Farmers observe, interact, and try to replicate technologies that have been implemented and are working for other farmers (Harvey *et al.*, 2013).

Despite the existence of the three farmer learning theories, more research is being invested in conducting adoption studies (Magruder, 2018; Feyisa, 2020). However, information on socio-economic factors that affect farmer knowledge on implementing introduced technologies is scantily documented (Macharia *et al.*, 2014; Stevenson *et al.*, 2014). This is despite prove that adoption of recommended agronomic innovations is influenced by farmers' level of knowledge and other household dynamics that affect decision making on whether to adopt an innovation (Okoba and De Graaff, 2005). In the process, farmers are introduced to formal type of knowledge which is more oriented to increasing crop production and overall gross margins (Šūmane *et al.*, 2018). This form of knowledge ignores the fact that farmers are rich in their local/informal knowledge that is practical with local relevance and explicitly interlinking the environmental, socio-economic, and their spiritual dimensions (Pretty, 2008).

Improvement of farmer knowledge is crucial for providing means to enhance soil fertility and increase agricultural productivity (Peterman *et al.*, 2014). However, access to new agronomic knowledge may not always result in farmers adequately utilizing it in crop production (Adolwa *et al.*, 2010). Besides, the knowledge might be available but inaccessible, outdated or considered unreliable by farmers hence not utilized (Sanginga and Woomer, 2009). Knowledge levels could also be influenced by simple demographic factors like age and sex of targeted farmers. For example, male and elderly farmers have been documented to be more experienced and knowledgeable than female and youthful farmers (Onweremadu and Mathews-Njoku, 2007). Contrastingly, elderly farmers are conservative on traditional knowledge and risk averse compared to youthful farmers who are more flexible and curious to try new innovations (Macharia *et al.*, 2014). Therefore, adopting a gender integrative research approach and encouraging participation in farmer-centered interventions (Waddington *et al.*, 2014) can help to understand their knowledge and training needs. This can help in predicting contextualized limitations and possibilities associated with adoption of new technologies by different farmer categories (Okoba and De Graaff, 2005).

## **2.7 Literature Gaps**

Studies on productivity, economic profitability, and soil fertility benefits of MBILI and doubled-up legumes using different intercropping components have been conducted in Kenya and Malawi, respectively. However, there is no documentation of an improved cereal-legume intercropping system involving alternation of more than one legume species. An improved cereal-legume innovation that can increase productivity of two legume species through an integrative association that does not compromise on maize yields but offering additive benefits like improving soil fertility, and farm economics is lacking for Babati, Tanzania. In addition, the effects that introduction of the new cropping system could have on household decision making regarding its adoption, use and control of associated benefits is not understood. Moreover, the effects of different socio-economic factors on farmer knowledge and how they would affect adoption of the innovation is not clear. Therefore, this study sought to bridge the above identified research gaps through experimenting on the viability and benefits of different cereal-legume innovations. In addition, assessment of how farmer households participating in testing these interventions tailored them to solve the challenge of low legume yield and climate variability in cereal-based systems was conducted.

## CHAPTER THREE: METHODOLOGY

### 3.1 Description of Study Area

The study was conducted in two agro-ecological zones of Babati District in Tanzania. The study area is located within latitudes  $-4.264^{\circ}$  S and longitude  $35.48^{\circ}$  E and an altitude of about 1635 m.a.s.l (Figure 3.1). Two experimental trials were set in Riroda and Sabilo villages in high rainfall midlands, laying between 1500 to 1950 m.a.s.l. and having a unimodal rainfall between 900-1100 mm per annum. Two more trials were set in farmer fields in Gallapo village located in low rainfall midlands laying between 1200 to 1500 m.a.s.l and receiving a unimodal rainfall of between 750-900 mm per year. Seasonal rainfall received between the 2019 and 2021 seasons was recorded using automatic weather stations installed in Sabilo and Gallapo villages. Installation of weather station was not done to Riroda considering the site receives similar weather patterns as Sabilo.

Babati District is characterized by smallholder mixed farming systems with a complex integration of livestock and food crops. Soils are dominantly Ferralsols and characterized by limitation of N and P nutrients (Adu-Gyamfi *et al.*, 2007), and micronutrients like Zn and Mn in some regions. Land holding ranges between 1 to 2 hectares in the high rainfall midlands and 3 to 10 hectares in low rainfall midlands (own data). Maize is the major crop cultivated mainly for subsistence purpose and extra sold for commercial use. Pigeon pea and beans are the dominant legumes. Pigeon pea is mainly cultivated for export while beans are grown for household consumption and surplus sold in local markets. Average maize yield is  $2.8 \text{ t ha}^{-1}$ ,  $0.7 \text{ t ha}^{-1}$  for pigeon pea and  $0.24 \text{ t ha}^{-1}$  for common beans (Laizer *et al.*, 2019; Mugi-Ngenga *et al.*, 2021), with the two legumes being cultivated under cereal-based intercropping.

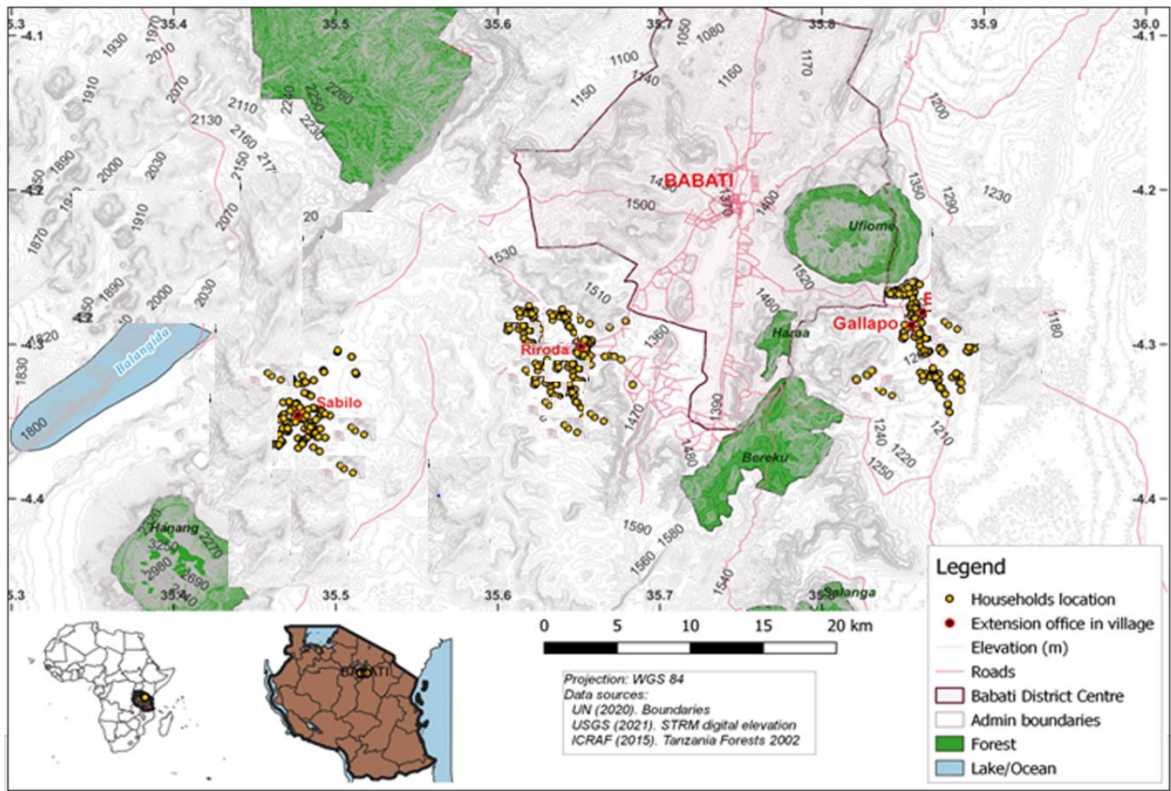


Figure 3.1: Map showing Babati District and the three villages where study was conducted.

### 3.2 Research Design

Experimental trials were used to address objectives 1, 2 and 3 while farmer surveys were used to collect data for addressing objectives 4 and 5.

#### 3.2.1 Experimental Design

Experimental trials were laid in a randomized complete block design with three replicates and seven treatments set on plots measuring 5 m × 7 m. Trials were set in two randomly selected fields for each of three villages (Gallapo, Riroda and Sabilo) between the 2018 and 2021 rainy seasons. This specific study commenced in 2020 season but uses agronomic data previously collected in the 2018 and 2019 seasons. No changes in the experimental layout were made except introduction of a farmer’s practice during the 2020 cropping season. Trials were researcher-designed with some level of farmer involvement to stimulate exposure and preparedness for participatory testing exercise in their own fields. Maize, beans, and pigeon pea were established following conventional intercropping system, as doubled-up legume and Mbili-Mbili (Table 3.1; Figure 3.2). Maize was spaced at 90 cm × 25 cm and pigeon pea at

90 cm × 50 cm between maize rows. For Mbili-Mbili system, two maize rows (50 cm × 25 cm) were alternated with two pigeon pea rows and a row of beans sneaked between the duo pigeon pea rows. In doubled-up legume system, beans were spaced at 45 cm × 15 cm and intercropped with pigeon pea at 90 cm × 50 cm. For all systems, planting was conducted using hand hoes. Except for the treatment where Meru H513 maize variety (with erectophiled leaves) was planted (i.e., treatment 7), Syngenta H624 variety (with Planophiled leaves) was planted throughout the study period. Bean variety under doubled-up legume and Mbili-Mbili treatments was Jesika. During the 2020 and 2021 seasons, a second bean phase was sown after harvesting the first phase to take advantage of residual moisture and low pigeon pea canopy.

Table 3.1 Description of the treatments

#	Treatment description
1	Continuous maize planted at 25 cm by 90 cm. No legume; <i>Rotated with Treatment 4 in season 2</i>
2	Maize planted at 25 cm by 90 cm and pigeon pea at 50 cm between maize rows. <i>No de-topping</i>
3	Maize planted at 25 cm by 90 cm and pigeon pea at 50 cm between maize rows. <i>Maize de-topped at physiological maturity</i>
4	Bean-pigeon pea intercropping (Doubled-up legume) <i>Rotated with Treatment 1 in season 2</i>
5	Maize planted at 50 cm by 90 cm (2 plants per hill) and pigeon pea at 50 cm between maize rows. <i>Maize de-topped at physiological maturity</i>
6	Two rows of maize (planted at 25 cm by 30 cm by 150 cm), 1 row of beans between 2 rows of pigeon pea (“Mbili-Mbili intercropping”). <i>Bottom leaves stripped</i>
7	Meru H513 maize planted at 25 cm by 90 cm and pigeon pea between maize rows. <i>No de-topping. Maize variety has vertical leaf architecture</i>
8	Farmer practice

Maize with planophiled leaves were planted in all treatments and seasons except treatment 7 where an erectophiled-leaf Meru H513 variety was planted. For pigeon pea Mali (ICEAP 00053) variety was planted.

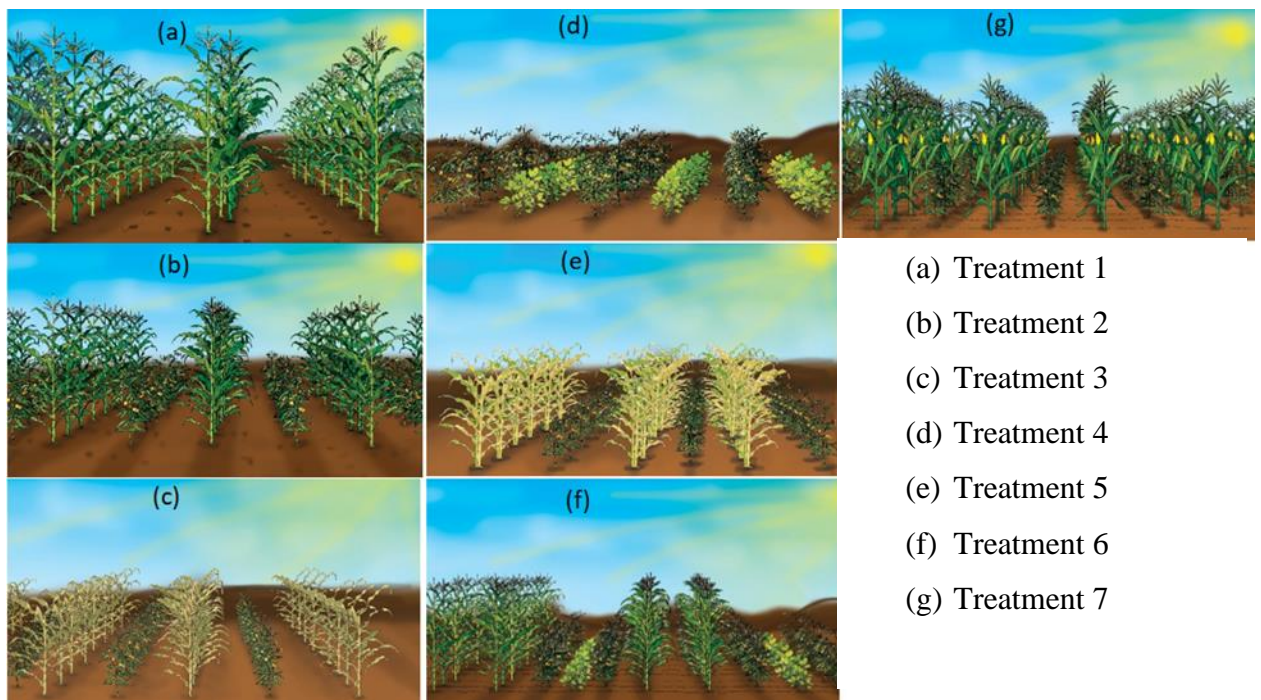


Figure 3.2. Illustrations of improved intercropping treatments tested during the 2018-2021 seasons in Babati.

### 3.2.2 Field Management Practices

Land preparation was conducted using tractors, the most common mode of land preparation in smallholder cultivation fields in Babati. Except for farmer practice, maize was applied with a uniform basal application of Minjingu Nafaka Plus at  $20 \text{ kg P ha}^{-1}$  and top-dressed with  $50 \text{ kg N ha}^{-1}$  of Minjingu Top-dressing fertilizer following the AfricaRISING project fertilizer recommendations (Kihara *et al.*, 2021). In addition to P, Minjingu Nafaka plus is blended with N (9%), K (6%), CaO (25%), S (5%), MgO (2%), Zn (0.5%) and B (0.1%) while apart from N, Minjingu Top dressing has  $\text{P}_2\text{O}_5$  (10%) and CaO (15%; Plate 3.1). Trials were weeded two times for each season using hand hoes while pest management was conducted immediately their attack on crops was identified following the standard procedures outlined by the Ministry of Agriculture in Tanzania.



Plate 3.1. Minjingu Nafaka Plus and Minjingu Top dressing fertilizers applied on maize.

### 3.3 Farmer Surveys

During initiation of this study, a group of 150 participants were selected from farmer inventories in the three targeted villages for participatory testing of Mbili-Mbili and doubled-up legume systems. A multi-stage, probability sampling method was used to derive the sample. For representativeness, farmers were stratified into three strata i.e., male and female, youthful (<35 years) and adult ( $\geq 35$ ) and household type (i.e., male-headed and female headed) farmers. Considering that the population of youthful and female-headed households was low across the villages, probability proportionate to size sampling was used to generate a representative sample for each category. In addition, a second criterion for selection was applied which was based on farmers consent, availability to participate and willingness to provide 0.1 ha portion of land for a baby trial set-up. Prior to commencement of each season, hands-on-training was provided on technical design of implementing Mbili-Mbili and doubled-up legume. Besides, farmers were also trained on the benefits and how to conduct good agronomic practices such as proper spacing, timely planting, weeding, pest management, harvesting etc., that would accompany the two technologies during their implementation. Selected farmers were allowed to choose either of the two technologies that they would wish to test in their home fields. Distribution of inputs i.e., seeds and fertilizers, was done

commensurate to the technology chosen by farmers. All along the cropping season, farmers received digital messaging services on their cellphones from a platform dubbed MWANGA that was developed to guide farmers through provision of real-time agronomic advisories. The messages were co-created by the researcher and extension staff to guide farmers on the good agronomic practices they needed to apply at each stage of crop growth. Later in the season, farmers also received agronomic advisory on general crop management during the annual field days that were organized in one mother trial per each of the villages.

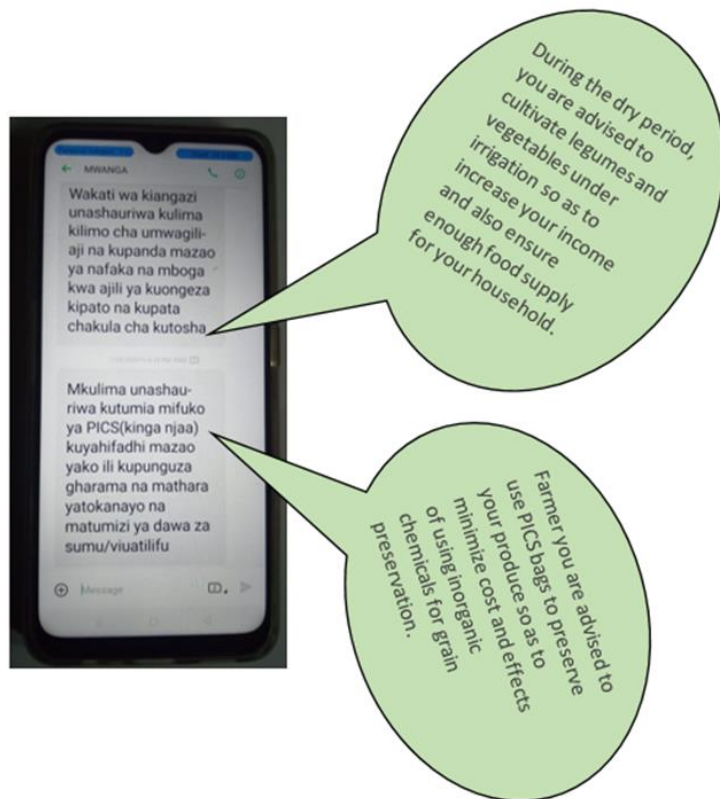


Plate 3.2. A message extract shared to farmers guiding on field usage, to ensure food and nutrient security, and post harvest handling of produce.

### 3.4 Assessing Economics of Improved Cropping Systems in Three Eco-Zones of Babati

Yield parameters i.e., stripped maize leaves, toppings, grain, and biomass weights were quantified and used for economic assessment of different treatments under study.

#### 3.4.1 Stripping and De-topping Activities

Removal of five bottom leaves of the maize i.e., leaf stripping, was conducted in Mbili-Mbili treatment at anthesis (50% silking) stage. The bottom most leaves which had already started

senescing were stripped off at the leaf collar i.e., between leaf sheath and maize stem. This procedure was done to increase light interception by understorey legumes i.e., pigeon pea, and bean planted in the second phase. In addition to leaf stripping, maize in treatments 3 and 5 were de-topped at physiological maturity using secateurs to avoid cob damage. The process was done by nipping the upper part of the maize plant about 10 cm above the ear leaf. Field weights of both the stripped leaves and maize toppings from a 3m × 3m net plot were also recorded. Strippings and toppings were chopped into smaller pieces, mixed for homogeneity and a sample collected, labeled, weighed, and transported to the laboratory for oven drying (at 60 °C) and dry weight determination for each of the two components.

#### ***3.4.2 Grain and Stover Yield Assessment***

For all crops under assessment, harvesting was conducted at physiological maturity. Crops were harvested from net plots measuring 3m × 3m and edge rows left to eliminate border effects. Maize and pigeon pea were cut at ground level while beans were uprooted, and field weights recorded. For the maize, cobs were separated from husks and total weight of cobs and stovers recorded. A sample of cobs and stover was collected for each of the plots by randomly selecting 5 cobs and stover (chopped and thoroughly mixed) and their field weights recorded (Kinyua *et al.*, 2021; 2023). Pods from pigeon pea and beans were also manually separated from haulms and total weights of both parameters weighted. A sample of pods and haulms was collected, weighed, labeled, and taken to the laboratory for dry weight determination. In the laboratory, samples were oven dried at 60 °C for 24 hours. Upon drying to a constant moisture, both the pods and cobs were threshed to separate grain from husks and cores, respectively. The dry weights of grain samples, husks, haulms, and cores were recorded and used to determine the overall yields, expressed in per hectare basis (Matusso *et al.*, 2014). Total yield was calculated using the Equation 3.1 by Mupangwa *et al.* (2007).

$$Y = \frac{Sdw}{Sfw} (1000) \times FW \times (10/A) \quad (\text{Eq. 3.1})$$

Where: Sdw = sample dry weight; Sfw = sample fresh weight; FW = field weight at net plot level; A = area of the net plot.

### ***3.4.3 Cropping Systems Economics***

Economic assessment was conducted on each of the treatments to examine their profitability over the four seasons. Total variable cost (TVC) was the cumulative cost incurred during land preparation, input purchase, labor for planting, weeding, pests and diseases management, de-topping, stripping, crop harvesting and post-harvest processing (Table 3.2). Cost for conducting field operations was obtained from interviewing local extension staff. Prices of fertilizers and agro-chemicals were got from agro-dealer outlets. Maize stover, bean residues and pigeon pea husks were included in overall economics because of their value as livestock fodder. Pigeon pea stalks are a major source of fuel and were valued at per animal drawn cart basis. Prices were recorded in Tanzanian shillings and converted into US dollars (US\$). One US\$ was trading at Tsh 2269 in 2018, 2251 in 2019, 2283 in 2020 and 2309 in 2021. Across trial sites and seasons, the following commodities had similar costs; 1 kg of bean seed at US\$ 0.4, 1 kg of pigeon pea seed at US\$ 0.3, threshing a bag of pigeon pea at US\$ 1.1, US\$ 2.2 for maize stover per 150 kg of animal drawn cart, and US\$ 1.1 for pigeon pea husks per 25 kg bag (*all these commodities are excluded from Table 3.2*). To relate the economic profitability of the different treatments with that under farmer management, crop yields were adjusted by a reduction factor of 10% (CIMMYT, 1988).

Table 3.2. Cost of labor, inputs and farm gate prices of parameters used to calculate economic profitability of different treatments between year 2018 and 2021 in Babati, Tanzania

Parameter	Price ranges (US\$)
Maize seed 2 kg	5.2-5.3
Minjingu Nafaka fertilizer per 50 kg bag	22.0-25.6
Minjingu Topdressing fertilizer per 50 kg bag	55.5-61.5
Labor cost (USD day <sup>-1</sup> )	1.8-2.6
Harvesting maize per 100 kg bag	0.7-0.9
Harvesting pigeon pea per 120 kg bag	2.5-3.0
Harvesting beans per 120 kg bag	2.2-2.7
Cost of pesticides per hectare	16.2-54.9
Threshing maize 100 kg bag	0.4-0.5
Threshing beans per 120 kg bag	1.1-1.4
Price of maize per 100 kg bag	15.2-43.6
Price of bean per 120 kg bag	52.9-127.3
Price of pigeon pea grain per kg	0.2-0.5
Price of bean residues in 25 kg bag	0.9-1.2
Price of pigeon pea Stalks per 65 kg Cart	6.5-9.2

#### 3.4.3.1 Maize Equivalent Yields

Maize and legume yields were converted into maize equivalent yields (MEY) to allow economic comparison of the cereal-legume and legume-legume systems using equation 3.2:

$$MEY = MY + \frac{LY \times LP}{MP} \quad (\text{Eq. 3.2})$$

Where MY= maize yield (kg ha<sup>-1</sup>), LY= legume yield (kg ha<sup>-1</sup>), LP= market price of 1 kg of legume (US\$ kg<sup>-1</sup>) and MP= market price for 1 kg of maize (US\$ kg<sup>-1</sup>).

#### 3.4.3.2 Measures of Profitability

Cropping systems' net profitability (NP) was calculated using equation 3.3

$$NP \text{ (US\$)} = \text{Gross income (GI)} - \text{Total variable cost (TVC)} \quad (\text{Eq. 3.3})$$

Total variable costs = cost of (seeds, fertilizer and agro-chemical applied, and local labor)

Gross income = farm gate prices of crop produce. Gross incomes (GI; \$ ha<sup>-1</sup>) were computed using farm gate prices of the crop produce.

Stability analysis for the different treatments across the different seasons was conducted using Shukla variance to establish the most viable treatment for recommending to farmers.

For VCR and BCR, economic analysis involved calculation of value/cost ratio and benefit/cost ratio as indicated in equation 3.4;

$$\text{VCR} = (\text{Gross benefit}) / ((\text{QBF} \times \text{PBF}) + (\text{QTF} \times \text{PTF})) \quad (\text{Eq. 3.4})$$

Where QBF= quantity of basal fertilizer applied at sowing, PBF= price of basal fertilizer applied at sowing, QTF= quantity of fertilizer applied at top-dressing and PTF= price of fertilizer applied at top-dressing.

$$\text{BCR} = (\text{Net returns}) / \text{TVC}$$

#### ***3.4.4 Data Analysis***

Considering that the measurements were conducted in four different seasons, repeated measures analysis of variance was used to assess for significant differences among the cropping systems. For the model, the different harvest seasons formed the variates, treatments were the different cropping systems while replicates nested within the three sites were the blocking structure of the model run in GenStat software version 14. For the beans, which were planted in only two cropping systems, descriptive statistics i.e., proportional differences of mean bean yield, were applied. A polynomial model i.e.,

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_h X_h + \varepsilon$$

Where Y is response to pigeon pea yield,  $\beta$  is the intercept,  $\beta_1$  to  $\beta_h$  are regression coefficients assigned to the independent variable ( $X_1$  to  $X_k$  i.e., quantity of maize toppings and strippings) and  $\varepsilon$  is the error term; was used to examine the potential influence of maize de-topping on pigeon pea grain and biomass yield. Separation of means was done using least significant difference (LSD) at  $p \leq 0.05$ .

### 3.5. Examining Effect of Different Cropping Systems on Biological Nitrogen Fixation Capacity of Intercropped Legumes

#### 3.5.1 BNF Assessment

Biological nitrogen fixation was assessed on the intercropped legumes for three growth seasons. In the 2019 season, pigeon pea samples were collected at mid-podding stage (50% podding) while pigeon pea grain and husks and bean haulms, grain and husk were sampled at harvest to assess N balances achieved through fixation and removals through grain and residue components. The  $^{15}\text{N}$  fixation balances was calculated using equation 3.5.

$$\text{Balance of } ^{15}\text{N Fixed (kg ha}^{-1}\text{)} = (\text{N}_{\text{PH}} + \text{N}_{\text{R}} + \text{N}_{\text{BH}}) - (\text{N}_{\text{PG}} + \text{N}_{\text{PP}} + \text{N}_{\text{BG}} + \text{N}_{\text{BP}}) \quad (\text{Eq. 3.5})$$

where N represents  $^{15}\text{N}$  fixed, PH is pigeon pea haulms, R is roots, BH is bean haulms, PG is pigeon pea grain, PP is pigeon pea husks, BG is bean grain and BP is bean husks.

In the 2020 and 2021 seasons, only N fixation by pigeon pea biomass at mid-podding was assessed. Pigeon pea samples were collected from a quadrant measuring 1 m x 1 m at plot level. Plants were cut 2 cm above the soil surface and total above ground biomass weights recorded. Soil-free biomass was chopped, thoroughly mixed and a sample collected for analysis. Root biomass was dug out and root nodules extracted and separated at 0-30 cm and 30-50 cm depths. Only the root component from 0-30 cm depth was sampled for BNF assessment. Maize stover within pigeon pea intercrop was sampled at maturity and used as the reference crop during determination of fixed N (van Vugt *et al.*, 2017). In the laboratory, pigeon pea roots were carefully washed using de-ionized water over 0.5 mm sieve (Kihara *et al.*, 2011b) and fresh weights determined. Samples were oven dried at 60 °C for 48 hours, weighed, milled using cyclotech mill over a 0.5 mm sieve and later ball milled to 0.2 mm size. Milled samples were shipped for BNF determination by  $^{15}\text{N}$  natural abundance method (Peoples *et al.*, 2002) in KU Leuven Laboratory in Belgium. Resulting data was used to calculate the proportion of Ndfa using equation 3.6.

$$\% \text{Ndfa} = 1 - (\text{Atom\% excess of pigeon pea}) / (\text{Atom\% excess of reference}) \times 100 \quad (\text{Eq. 3.6})$$

The amount of  $^{15}\text{N}$ -fixed by pigeon pea and beans was calculated using equation 3.7

$$\text{Amount of N fixed (kg ha}^{-1}\text{)} = (\% \text{Ndfa}/100) \times \text{Legume N} \quad (\text{Eq. 3.7})$$

### ***3.5.2 Leaf Litter Fall***

The quantity and quality of abscised pigeon pea leaves were assessed by electing wooden pegs within the net plots and mesh traps measuring 90 m × 1 m fitted 5 cm above the ground. Leaf litter samples were oven dried at 60 °C and dry weight assessed. Samples were ground using Cyclotec mill through 0.5 mm sieve. Ground samples were analyzed for N and P using wet oxidation method (McKenzie and Wallace, 1954).

### ***3.5.3 Partial Factor of Productivity***

Partial factor of productivity for both N and P were calculated using equation 3.8:

$$\text{Partial factor of productivity (PFP)} = \frac{Y \left(\frac{kg}{ha}\right)}{NS \left(\frac{kg}{ha}\right)} \quad (\text{Eq. 3.8})$$

Where Y is the yield in kg ha<sup>-1</sup> of treatment and NS is amount of nutrient supplied by fertilizer.

### ***3.5.4 Agronomic Efficiency***

Agronomic efficiency of N and P applied to the different treatments was calculated using equation 3.9.

$$\text{Agronomic efficiency (AE)} = \frac{Y_t \left(\frac{kg}{ha}\right) - Y_c \left(\frac{kg}{ha}\right)}{NS \left(\frac{kg}{ha}\right)} \quad (\text{Eq. 3.9})$$

### ***3.5.5 Data Analysis***

Repeated measures analysis of variance was used to assess for significant differences in BNF levels for the three seasons. For this model, sampling times were the variate; cropping systems formed the treatment structure while blocking structure was the replicates. In addition, one-way ANOVA was conducted to evaluate the quantity of abscised pigeon pea leaves and associated N fixation levels, the partial factor of productivity and agronomic efficiency between the cropping systems using GenStat. In the model, the quantity of abscised leaves and maize yield of fertilized cropping systems were the variates, treatment structure was the cropping systems while blocking structure was the three replicates nested within the trial sites.

## **3.6 Evaluating how Variations in Cropping Systems Influence Crop Physiological Characteristics and Physical-Chemical Properties of Soil in Three Eco-Zones of Babati**

### ***3.6.1 Leaf Area Index and Photosynthetically Active Radiation Assessment***

A 1 m x 1 m quadrant was randomly selected in the net plot, for all treatments. AccuPAR sensor probe was used to measure six readings staggered along the rows and another eight readings taken between the intra-row spaces. Beam fraction was recorded by an external sensor placed outside the plots, at least 0.5 m above the canopy. The leaf area index was directly recorded by the Ceptometer and used to assess effects of vegetation cover on soil moisture and temperatures under the different cropping systems. Plant canopy reflectance for each treatment was calculated using equation 3.10 (Koocheki *et al.*, 2016).

$$\text{PAR fraction } (\mu\text{molm}^{-2}\text{s}^{-1}) = (A_P - B_P)/A_P \quad (\text{Eq. 3.10})$$

Where  $A_P$  is the average photosynthetically active radiation above canopy and  $B_P$  is the average PAR below plant canopy

### ***3.6.2 Leaf Chlorophyll***

Measurements were recorded fortnightly on fully expanded leaves of ten randomly selected maize plants (Matsunaka *et al.*, 1997) from V6 stage to blister formation. The leaf chlorophyll measurements were taken using SPAD 502 Plus Chlorophyll Meter at plot level. Ten plants were randomly selected, and measurements taken on the leaf blade of a fully developed leaf.

### ***3.6.3 Soil Moisture and Temperature Assessment***

The effect of different plant spatial patterns on soil moisture and temperature in the different treatments were assessed from the period maize attained V6 stage (six fully expanded leaves) of development until pigeon pea maturity. A hand-held sensor i.e., TEROS 12, was plugged on Em50 ProCheck device (Decagon Devices Inc.) to measure soil physical parameters. The sensor has three probes that records soil moisture (0.00–0.70  $\text{m}^3/\text{m}^3$ ) and temperatures (–40 to 60 °C). Measurements were taken at five randomly selected points within the net plot.

### ***3.6.4 Soil Sampling and Analysis***

Soil was sampled at four randomly selected points in each of the replicate using Y- method. Samples were collected at 0-20 cm depth using soil auger, mixed for homogeneity, and taken to the laboratory. Samples were oven dried (60 °C), ground through 2-mm sieve, coned and quartered for analysis. Soil extractable P, S, Zn, Mn, B, and Fe was determined by wet chemistry method based on Mehlich 3 extraction procedure (Mehlich, 1984), K using flame photometer (Jackson, 1993) while exchangeable Ca and Mg using atomic absorption spectrophotometry (Welz and Sperling, 2008). Cation exchange capacity was assessed using NH<sub>4</sub>-acetate leaching (Schollenberger and Simon, 1945) and pH in 1:2.5 soil: water. Total C and N were assessed by total combustion technique (Duma's combustion) using an elemental macro-analyser (Elementar Vario Max Cube; Bremner and Tabatabai; 1971).

### ***3.6.5 Data Analysis***

Plant physiological and soil physical parameters sampled at multiple times within a cropping season was assessed using repeated measures analysis of variance in GenStat. Sampling times were the variate; cropping systems formed the treatment structure while blocking structure was the replicates nested within the trial sites. Separation of means was done at  $P \leq 0.05$ .

## **3.7 Assessing the Influence of Farmer Gender on Agricultural-Based Decisions**

### **Making Process on Implementation of Improved Cropping Systems**

#### ***3.7.1 Technology Rating***

During the third season of technology testing, local farmers were invited to rate the new agronomic innovations in the researcher designed and managed trials. Farmer invitation was open to participants across gender and age groups. The invitation was conducted through phone calls and facilitated by lead farmers who were guided by the village extension staff.

The farmer rating activity was conducted in one of the fields hosting experimental trials (per village) and the process facilitated by the researcher with the help from District extension staff. During the exercise, farmers were organized in small groups composing pure male and female participants, group leaders were selected, and matrices (Appendix 1 and 2) used during rating of the different treatments. Intercropping technologies i.e., treatments, under experimental trial were masked using dummy identifiers and farmers allowed to observe and

indicate the suitability of each technology based on the four sustainable intensification (SI) indicators i.e., productivity, economics, social (labor) and human domains (Musumba *et al.*, 2017). Each farmer group conducted ranking and rating of the different technologies and indicated reasons guiding their ranking/rating and constraints associated with implementation of each technology. The rating scores were 100% (Very good); 75% (Good); 50% (Average); 25% (poor). Technology ratings by farmers of same sex were pooled to help understand sex disaggregated perspectives towards each intercropping technology. To determine the final rating, scores for each SI indicators were summed and averaged as shown in equation 3.11:

$$T_{\text{rank}} = (S_{\text{yld}} + S_{\text{prof}} + S_{\text{lab}} + S_{\text{fs}}) / 4 \quad (\text{Eq. 3.11})$$

Where  $T_{\text{rank}}$  is the final rating of the technology,  $S_{\text{yld}}$  is the systems' productivity score,  $S_{\text{prof}}$  is profitability score,  $S_{\text{lab}}$  is the labour score and  $S_{\text{fs}}$  is the food security score.

### **3.7.2 Household Surveys**

The participant farmers (recruited as described in Section 3.3) were supported in implementing trials consisting of either Mbili-Mbili or doubled-up legume in their own fields. In addition, they were taken through sets of trainings, on how to design the two innovations and the accompanying good agricultural practices, that were done throughout the study period. Between October-November 2020, a survey was conducted to assess how introduction of Mbili-Mbili and doubled-up legume systems were influencing decision making within participating farmers' household, labour productivity and how income emanating from introduced systems were controlled. A survey tool was developed and pretested in 4 households per village following the guidelines by Sudman (1983). The tool was uploaded in SurveyCTO, a mobile data collection interface for digital roll-out.

Data targeted during this survey included household socio-economic characteristics and how field activities involving Mbili-Mbili and doubled-up legume were implemented. To understand the influence of introduced technologies on farmer households, questions relating to who made decision on how specific field activities would be conducted as well as who assigned and/or implemented specific agronomic roles were asked. In addition, a control group consisting of 32 farmers (determined as the probable proportion to the 150 sample of participants) who were not directly involved in the project was included in the survey.

### ***3.7.3 Data Analysis***

Categorical data was subjected to chi-square tests while the numeric (continuous data) was subjected to One-way ANOVA at  $P \leq 0.05$  confidence level to compare farmer characteristics across sites. Household characteristics i.e., gender, marital status, education etc., associated with implementing Mbili-Mbili and doubled-up legume were analyzed by descriptive statistics (i.e., averages, standard deviations and proportions) to identify major attributes influencing decision making. Correspondence analysis (CA) was used to simultaneously examine the relationship between decision-makers for different farm activities under doubled-up legume and Mbili-Mbili. The R package ‘ca’ was used to explore the structural relationships of different farm level decisions (i.e., relating to farm operations) against the household decision makers (husband, wife, husband + wife or other household members). Multi-variate method was used to explore the relationship between household membership and control of income from each of the component crops (maize, bean and pigeon pea).

## **3.8 Socio-economic Factors Affecting Farmer Knowledge on Implementing Improved Cropping Systems**

### ***3.8.1 Rating of Farmer Knowledge***

At the end of the 2020 season, an assessment was done to examine the early patterns of knowledge acquisition after a rigorous farmer engagement and their involvement in implementing Mbili-Mbili or doubled-up legume. The assessment was targeted on all farmers involved in technology testing. A control group was not included in this study because only farmers who had participated in trainings organized during the study could comprehend and articulate knowledge facets involving the two innovations. The scope of this study was to examine farmer knowledge and extent of utilization of agronomic knowledge around ISFM, good agronomic practices and extension services within and beyond Mbili-Mbili and doubled-up legume trials.

The farmer knowledge assessment tool had two major sections. The first section was a Likert scale of 36 items where farmers indicated ratings of their perceptions of effectiveness and value of pieces of training conducted during their engagement, their knowledge after the training, and extent of applying the acquired knowledge. The questions included the above aspects with respect to the two technologies, timely planting, certified seeds, fertilizer use,

manure utilization, pest and disease control, soil and water conservation and extension advisory.

A second section had a five level Likert scale of 20 positively stated constructs i.e., 1= strongly disagree, 2= disagree, 3= not sure, 4= agree, and 5= strongly agree. The constructs were used to examine farmer knowledge of good agricultural practices, and their understanding of the technical aspects associated with implementation of Mbili-Mbili and doubled-up legume (Table 3.4). The constructs captured farmer understanding on design of the two technologies and their knowledge of soil fertility management, pest and disease management and enacting soil and water conservation measures.

Table 3.3: Agronomic knowledge themes on Mbili-Mbili and doubled-up legume technologies in Babati, Tanzania

Implementing the new technology	General agronomic practices	Soil fertility management	Pest and disease control	Soil and water conservation
<p>-In Mbili-Mbili, beans are planted adjacent to the double maize rows</p> <p>- In Doubled-up legume, beans and pigeon pea can be planted on same day</p> <p>- Two bean phases can be planted in Mbili-Mbili/Doubled-up legume within a season</p> <p>-Mbili-Mbili does not result to competition among intercropped plants</p> <p>-Mbili-Mbili has similar maize rows as conventional system</p> <p>-Mbili-Mbili increases light penetration to understorey legumes</p> <p>-Mbili-Mbili/Doubled-up legume are risk averse than Conventional intercrop</p> <p>-In Mbili-Mbili, pigeon pea does not shade the bean crop</p> <p>-Mbili-Mbili-increases food secure months</p>	<p>-Proper spacing using gardeners line increases plant population than planting behind plough</p> <p>-Certified seeds increase yields</p> <p>-Timely planting maximizes use of soil moisture</p>	<p>-Top-dressing can be conducted even if maize was not applied with fertilizer at sowing</p> <p>-Basal fertilizer can be applied at sowing even if maize is to be top-dressed</p> <p>-Fertilizers and manure can be applied together</p> <p>-Pigeon pea leaf fall increases soil fertility</p> <p>-Cereal-legume rotations increase maize production</p>	<p>-Crop rotation breaks pest and disease cycles</p> <p>-Timely pest and disease control increases crop yields</p>	<p>-Pigeon pea roots help to break hard pans in soil</p> <p>-Pigeon pea provides soil cover</p> <p>-Pigeon pea roots prevent soil erosion</p> <p>-Compaction by livestock grazing in crop fields destroys soil structure</p> <p>-Pigeon pea crop keeps off livestock from crop fields</p>

*Note: Similar constructs relating to Mbili-Mbili and doubled-up legume have been merged and those that are different have been separated during presentation. As a result, a total of 24 constructs have been produced from the 20 original items.*

### 3.8.2 Data Analysis

The internal reliability of the constructs used to examine farmer knowledge on Mbili-Mbili, and doubled-up legume was tested using Cronbach's alpha coefficient (Cronbach, 1951) in SPSS. Constructs assessing knowledge on Mbili-Mbili had a Cronbach coefficient alpha of 0.7 while doubled-up legume had 0.87. This signified that the constructs were consistent and reliable for knowledge assessment. Principal Components Analysis (PCA) was used to isolate latent constructs that explained the underlying knowledge patterns. Multivariate analysis was run to examine the knowledge structure and associations within the knowledge themes. Original variables were reduced into a few uncorrelated (orthogonal) dimensions and the data scaled using zero-centered means. A correlation matrix was used for decomposition. Varimax rotation with Kaiser normalization procedure was applied to produce a factor pattern with highly significant variables loaded into a single factor. Factors were retained for interpretation when Eigen values were greater than 1. For effective interpretation of variables in the rotated component matrices, a loading cut-off point of 0.4 was used (Comrey and Lee, 1992).

After averaging knowledge scores for variables contributing to independent knowledge factors, four regression models in the form of equation 3.12 emerged i.e.,

$$Y' = A + B_1X_1 + B_2X_2 + \dots + B_kX_k + e \quad (\text{Eq. 3.12})$$

Where  $Y'$  is farmer knowledge i.e., have (no) knowledge of the predictor variables,  $A$  is the intercept,  $B_1$  to  $B_k$  are regression coefficients assigned to each independent variable (age, sex, marital status, education belonging to group, land size technology design and management practices) i.e.,  $X_1$  to  $X_k$  and  $e$  is the error term.

Since the type of household i.e., household headship, and sex of respondent farmer had a multicollinearity effect, the latter was a stronger predictor of farmer knowledge, hence used as a predictor variable in the glm regression models.

## CHAPTER FOUR: RESULTS AND DISCUSSION

### 4.1 Prevailing Weather of the Study Sites

The amount and distribution of rainfall varied during the four seasons of study and across the sites. Despite having a good rainfall distribution, the 2021 season received the lowest amount of rainfall (404 mm). This was contrary to the 2019 season which had moderate rainfall (542 mm) but with poor distribution. In-season dry spells exceeding beyond 2 weeks that started days after seed germination were also recorded in the 2019 season (Figure 4.1). The 2020 season also had a good distribution of rainfall of about 1565 mm. Despite receiving low rainfall, the 2021 cropping season had high levels of humidity (76.4%), though not as high as in 2020 (81.2%), as opposed to 2019 season when the lowest humidity rates (72.6%) were recorded. Poor rainfall distribution and amounts coupled with low humidity and high solar radiation  $121 \text{ W/m}^2$  contributed to the low crop performance in the 2019 season relative to the other cropping seasons.

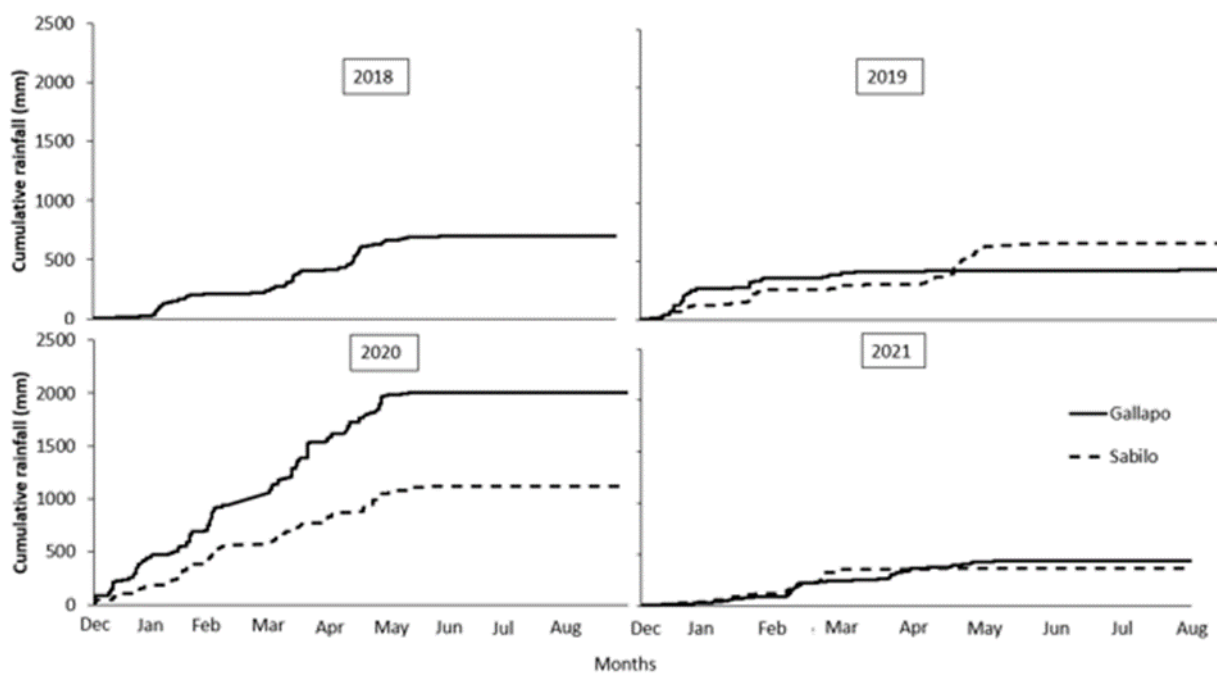


Figure 4.1: Cumulative rainfall in Gallapo and Sabilo sites. Rainfall data for the 2018 season was obtained from the NASA POWER ([visit nasa.gov](http://www.nasa.gov)) because weather stations were installed in 2019. Data from NASA POWER could not show variation in climate data for the two sites because they are within  $0.5 \times 0.625$ -degree resolution (within 50 km radius)

Seasonal weather variations affect the attainable yields under rainfed systems like those of this study. Babati District has undulating terrain that contributes to existence of sharp rainfall, temperature, and soil fertility gradients. The heterogeneity in landscape configuration compounded by the current variable weather conditions might have promoted the occurrence of variable seasonal weather in the different sites. A similar variability in seasonal weather attributed to topographical alignment of the landscape were reported by Mugi-Ngenga *et al.* (2023) within the same study area with dry spells stretching between 40 – 70 days and coinciding with vegetative development of crops. Some areas of Babati such as Riroda have soils with low clay content (12%) and sandy texture (67.3%) that could amplify the weather variability effects, especially during poor seasons, with a potential of crop failure (Msigwa, 2018; Mugi-Ngenga *et al.*, 2022a). Antwi-Agyei *et al.* (2021) proposed the need for provision of timely and accurate climate information to guide farmers on proper timing of field operations and choice of suitable varieties for different seasons to enhance their resilience.

#### **4.2 Initial Soil Nutrient Characterization of the Study Site**

Soils of the sites had a moderate pH of between 6.3 – 7.0 (Table 4.1) and had deficiency in soil N (>0.1) and C (>1.3). Soils in Riroda village showed deficiency in the highest number of nutrients including P (6.6 ppm), Zn (1.0 ppm), B (0.3 ppm) and S (15.5). The content of P (21.7 ppm) and Zn (1.4) in soil samples collected from Sabilo village were also low.

Table 4.1. Soil nutrient levels in experimental fields located in Riroda, Sabilo and Gallapo villages of Babati District

Nutrient	Riroda	Sabilo	Gallapo
Soil pH (1:2.5 soil: H <sub>2</sub> O)	6.5 (0.2)	6.3 (0.4)	7.0 (0.3)
%N	0.1 (0.02)	0.1 (0.03)	0.1 (0.04)
P (Olsen)	6.3 (6.6)	21.7 (25.4)	72.8 (30.8)
K (ppm)	236 (88.6)	1092 (628)	414 (430)
%C	0.8 (0.4)	1.3 (0.2)	1.1 (0.4)
S (ppm)	15.5 (5.7)	31.7 (4.8)	31.1 (9.9)
Cu (ppm)	2.6 (0.8)	11.5 (0.2)	7.8 (3.5)
Zn (ppm)	1.0 (1.1)	1.4 (3.4)	15.4 (7.5)
B (ppm)	0.3 (0.1)	0.9 (0.3)	0.6 (0.2)
Fe (ppm)	169 (13.1)	156 (45)	296 (64)

*Values in brackets are standard deviations.*

The challenge of soil nutrient degradation in smallholder systems of the study area was evident by the dominant deficiency in soil N and P. Limitation of P can be attributed to soils of the study area being Ferralsols, which mainly fixes the nutrient to forms that are inaccessible by plants. Low adoption rates of fertilizers in the study area and complete removal of residues after crop harvest to feed livestock in homefields (Jindo *et al.*, 2020) might have contributed to mining of N, resulting in its deficiency. Deficiency of N and P nutrients can be associated with low maize yields of about 2 t ha<sup>-1</sup> reported in the study area (Kihara *et al.*, 2015a), despite a potential production of up to 6 t ha<sup>-1</sup> (Kinyua *et al.*, 2023). Application of inorganic fertilizers with a key consideration of the two nutrients can be an important strategy for unlocking yields in Babati (Makoi, 2016; Bekunda *et al.*, 2022), as is the case with other smallholder systems in SSA (Kinyua *et al.*, 2021). Indeed, Kihara *et al.* (2021) reported fertilizer response where application of modest N and P rates of 50 and 20 kg ha<sup>-1</sup>, respectively, resulted in upto 214% increase in maize yield over unfertilized farmer practices.

Results of this study indicates the need for blending the locally available macronutrient fertilizers with micro and secondary nutrients to provide S, Zn, B, which were also found to be limiting in the area. Secondary and micronutrients were especially found to be limiting in Riroda village with S, Zn and B levels being below the recommended thresholds of 30 ppm

(Palaskar and Ghosh, 1985), 2 ppm (Sims and Johnson, 1991), and 0.5 ppm (Aref, 2011), respectively. The sandy nature of the soil in Riroda, also reported by Mugi-Ngenga *et al.* (2023), might have resulted in low nutrient holding capacity exposing them to losses through erosion and leaching. The problem of micronutrient deficiencies is not solely new to the study area but has been reported to be widespread in smallholder systems of SSA. For example, Zn, S and B were reported by Vanlauwe *et al.* (2015) as limiting in Ethiopia while Zn and S was limiting in multiple sites in Malawi (Botoman *et al.*, 2020; 2022). In agreement with results from this study, Kihara *et al.* (2020) recommended formulation of micronutrient-rich fertilizer blends that will not only help to boost crop yields but also improve the quality of produce. This can also help in averting nutritional burdens, such as hidden hunger, that are pronounced in poorly resource endowed households (Gödecke *et al.*, 2018; Gashu *et al.*, 2021).

This study revealed the eminent need for applying interventions that could help to improve soil organic C, which was dominantly below the critical levels (<2%) and that plays an important role in promoting the general soil health. Employment of poor agricultural practices such as continuous soil disturbance through tillage, residue removal, post-harvest grazing and application of low quantities of manure at reduced frequencies might have enhanced soil organic carbon loss. However, adoption of strategies such as addition of organic amendments like crop residue retention in the field, manure application, cover cropping, minimizing soil disturbances through embracing conservation agriculture can help to improve the soil C levels. This is because soil organic matter plays a key role in soil nutrient conservation and enhancing proliferation of soil fauna which helps in nutrient turn-over. Results from this study agrees with those of Kihara *et al.* (2015a) who reported up to 100% of residue removal from crop fields to feed livestock in homefields which encourages loss of organic matter in the out-fields. Other studies (Owenya *et al.*, 2011; Kizito *et al.*, 2016) have also documented the detrimental effects of on-field communal grazing on soil structure degradation including destruction of soil and water conservation structures and posing challenges to adoption of conservation agriculture and agroforestry practices. Sensitization on the need to avoid post-harvest grazing to improve soil structure and soil organic matter while reducing soil erosion can help to avert the situation (Teklewold *et al.*, 2020). In addition, application of manure and introduction of innovative system approaches can also help in recovery of mined nutrients in such an area that is characterized by low fertilizer usage (Kihara *et al.*, 2021).

### **4.3. Economics of Improved Cropping Systems in Gallapo, Sabilo and Riroda Villages of Babati**

#### ***4.3.1 Maize Grain Yield***

Generally, maize grain yield was significantly affected by site and by treatments ( $P \leq 0.05$ ). Treatment effects were visible in the 2020 season where farmer practice had lower ( $P \leq 0.05$ ) maize grain yield than the improved practices, and in the 2021 season where sole maize system had higher ( $P \leq 0.05$ ) grain yield than treatments with/without maize de-topping and the farmer practice (Table 4.2). Despite having more than two species of crops, Mbili-Mbili system had similar maize yields as other cereal-legume intercropping practices having only two crop components. Like maize grain component, improved practices had significantly higher ( $P \leq 0.05$ ) stover yield than the farmer practices in the 2020 and 2021 seasons. During the 2021 cropping season, treatments where maize was de-topped had significantly higher maize stover yields than those with no de-topping.

Table 4.2. Maize grain and stover yield produced between the 2018 and 2021 seasons in Babati, Tanzania

Treatment	Year			
	2018	2019	2020	2021
<i>Maize grain yield (t ha<sup>-1</sup>)</i>				
Sole maize	2.4 <sup>a</sup>	2.0 <sup>a</sup>	6.2 <sup>a</sup>	5.5 <sup>a</sup>
Maize no de-topping	2.4 <sup>a</sup>	1.8 <sup>a</sup>	5.4 <sup>a</sup>	3.9 <sup>b</sup>
Maize de-topped	2.1 <sup>a</sup>	1.8 <sup>a</sup>	6.0 <sup>a</sup>	4.4 <sup>b</sup>
Doubled-up legume				
Maize 2 plants per hill	2.2 <sup>a</sup>	1.4 <sup>a</sup>	5.5 <sup>a</sup>	4.6 <sup>ab</sup>
Mbili-Mbili	2.0 <sup>a</sup>	1.7 <sup>a</sup>	5.9 <sup>a</sup>	4.6 <sup>ab</sup>
Meru 513	2.4 <sup>a</sup>	1.9 <sup>a</sup>	6.1 <sup>a</sup>	4.5 <sup>ab</sup>
Farmer Practice <sup>€</sup>	-	-	2.4 <sup>b</sup>	2.8 <sup>c</sup>
<b>LSD</b>	0.47	0.75	1.27	1.13
<b>P-Value</b>	0.21	0.714	0.001	0.001
<i>Maize stover<sup>α</sup> yield (t ha<sup>-1</sup>)</i>				
Sole maize – DUL rotation <sup>¥</sup>	1.9 <sup>a</sup>	3.3 <sup>a</sup>	6.9 <sup>a</sup>	5.2 <sup>ab</sup>
Maize no de-topping	1.9 <sup>a</sup>	2.8 <sup>a</sup>	6.4 <sup>a</sup>	4.2 <sup>bc</sup>
Maize de-topped	1.4 <sup>a</sup>	3.0 (20.0) <sup>a</sup>	6.6 (30.3) <sup>a</sup>	4.5 (32.8) <sup>a</sup>
Doubled-up legume				
Maize 2 plants per hill	1.7 <sup>a</sup>	2.8 (17.6) <sup>a</sup>	5.1 (26.1) <sup>a</sup>	4.6 (31.3) <sup>a</sup>
Mbili-Mbili	1.7 <sup>a</sup>	2.7 <sup>a</sup>	6.0 <sup>a</sup>	5.0 (12.3) <sup>ab</sup>
Meru 513	1.9 <sup>a</sup>	2.9 <sup>a</sup>	5.3 <sup>a</sup>	5.2 <sup>ab</sup>
Farmer Practice <sup>€</sup>	-	-	2.2 <sup>b</sup>	2.7 <sup>c</sup>
<b>P-Value</b>	0.673	0.434	0.001	0.001
<b>LSD</b>	0.72	0.87	1.45	1.39

<sup>€</sup>Treatment assessed only in the 2020 and 2021 cropping seasons. <sup>a</sup> toppings and strippings are presented in parentheses as proportions of stover yield obtained at harvest; During statistical analysis, toppings and strippings were added to the harvested stover biomass. Values within the same column and followed with different letters are significantly different.

In the current study, doubling and tripling of maize grain and stover yield over the farmer practice was attained through application of fertilizer recommendation rates of 20 kg P ha<sup>-1</sup>

and 50 kg N ha<sup>-1</sup>. Farmers in the study area are yet to embrace the use of fertilizers which they associate with '*destroying the soil*'. The high prices of fertilizers also compound the challenge of fertilizer accessibility and affordability hence the low usage by resource constrained households. In addition, use of good agronomic practices such as proper spacing and pest and disease management might have contributed to increase in maize yield relative to farmer practices. This is because improved systems have proper spacing while farmer practices in the study area are planted through broadcasting seeds behind tractor and animal drawn ploughs and rarely achieve the recommended 53,333 plants per hectare. Seed broadcasting is not only uneconomic since more seeds are utilized, but most of the seeds are deeply buried limiting chances of successful emergence. The potential of bridging maize yield gaps through adoption of ISFM practices has not only been reported in this region (Kihara *et al.*, 2020) but also in other parts of SSA (Kinyua *et al.*, 2021; Mbanyele *et al.*, 2021). However, Mugi-Ngenga *et al.* (2021) reported inter row spacing ranging from 0.6 m to 1.15 m and intra-row spacing of 0.25 m to 0.75 m attributed to seed broadcasting behind the plough. Ensuring proper planting depth should be promoted to optimize plant population and overall crop yield (Virk *et al.*, 2020; Kimmelshue *et al.*, 2022). Moreover, more sensitizations and trainings are needed to ensure farmers adopt multiple combinations of ISFM, such as inorganic fertilizers which is reported at <9% (Adu-Gyamfi *et al.*, 2007) and manure utilization at 60% (Kihara *et al.*, 2023; Mponela *et al.* 2023), to unlock the widespread yield gap under smallholder systems.

Significant grain yield increase in sole maize treatment in 2021 season following a season under pure legume i.e., doubled-up legume, in 2020 season was observed and attributed to utilization of residual nitrogen emanating from biological fixation by the legume phase. Rotation of maize monocrop system with doubled-up legume system can be considered as a good strategy for replenishing soil nutrients in resource constrained smallholder systems. Studies (Altieri *et al.*, 2018; Tariq *et al.*, 2019) have reported positive grain yield increases on subsequent cereal crop following a legume phase. However, a study by Kinyua *et al.* (2023) informed on the importance of increasing farmer access to climate information services that guides on appropriate seasons for implementing monoculture systems such as sole maize and doubled-up legume. This is because monoculture systems are vulnerable to seasonal weather variability hence yield loss, which exposes smallholder farmers to food insecurity risk (Altieri *et al.*, 2015; Tariq *et al.*, 2019).

In this study, different spatial configurations have been implemented while ensuring that population density of maize plants is not affected. Despite the large space created to improve access of light by understorey legumes under Mbili-Mbili, the system produced higher grain and stover yield than the farmer practice. Mbili-Mbili also had similar grain and stover yield, while some seasons had (non-significantly) higher yield than other improved practices. The performance of Mbili-Mbili during this study helps to overrule doubts on probability of reduced maize yields due to complexity of the intercropping components. Madembo *et al.* (2020) indicated conventional 2:1 intercropping systems as having similar maize yield as sole maize systems but documented their effect on reducing legume yield, hence a need for a double-row strip cropping system like Mbili-Mbili innovation. Interestingly, the novel Mbili-Mbili system increased the production of intercropped legumes without compromising yield of the maize main crop (Kinyua *et al.* 2023). In addition, the innovation allows for stripping and de-topping of maize, providing upto 2 t ha<sup>-1</sup> of in-season forage that is significantly richer in crude protein than unstripped forage (Komarek, 2021). Like studies conducted by Katsaruware and Manyanhaire (2009) and Raza *et al.* (2020) stripping and de-topping had no significant effect on maize yield but could increase yields of the intercropped legumes.

#### ***4.3.2 Legume Yield***

Treatment effects on pigeon pea grain yield was only visible in the 2020 and 2021 seasons (Table 4.3). In the 2020 season, doubled-up legume and the farmer practice had higher pigeon pea yield than the other treatments while in 2021 the same treatment had the highest ( $P \leq 0.05$ ) pigeon pea yield overall. Mbili-Mbili treatment attained similar level of pigeon pea yields i.e., for the grain and aboveground biomass, as other treatments having maize as the main crop.

Table 4.3. Pigeon pea grain and biomass yields between the 2018 and 2021 seasons in Babati, Tanzania

Treatment	Year			
	2018	2019	2020	2021
<i>Pigeon pea grain yield (t ha<sup>-1</sup>)</i>				
Sole maize	-	-	-	-
Maize no de-topping	0.37 <sup>a</sup>	0.37 <sup>a</sup>	0.49 <sup>b</sup>	0.89 <sup>b</sup>
Maize de-topped	0.40 <sup>a</sup>	0.38 <sup>a</sup>	0.45 <sup>b</sup>	1.03 <sup>b</sup>
Doubled-up legume	0.43 <sup>a</sup>	0.42 <sup>a</sup>	0.96 <sup>a</sup>	2.14 <sup>a</sup>
Maize 2 plants per hill	0.37 <sup>a</sup>	0.38 <sup>a</sup>	0.56 <sup>b</sup>	1.13 <sup>b</sup>
Mbili-Mbili	0.29 <sup>a</sup>	0.40 <sup>a</sup>	0.51 <sup>b</sup>	1.30 <sup>b</sup>
Meru 513	0.41 <sup>a</sup>	0.38 <sup>a</sup>	0.62 <sup>ab</sup>	1.03 <sup>b</sup>
Farmer Practice <sup>€</sup>	-	-	1.01 <sup>a</sup>	1.02 <sup>b</sup>
<i>P-Value</i>	<i>0.319</i>	<i>0.941</i>	<i>0.01</i>	<i>0.001</i>
<i>LSD</i>	<i>0.132</i>	<i>0.113</i>	<i>0.268</i>	<i>0.502</i>
<i>Pigeon pea aboveground biomass yield (t ha<sup>-1</sup>)</i>				
Sole maize	-	-	-	-
Maize no de-topping	5.9 <sup>a</sup>	1.5 <sup>ab</sup>	2.7 <sup>b</sup>	4.6 <sup>bc</sup>
Maize de-topped	4.9 <sup>a</sup>	1.4 <sup>a</sup>	2.6 <sup>b</sup>	5.4 <sup>b</sup>
Doubled-up legume	6.2 <sup>a</sup>	2.1 <sup>b</sup>	6.7 <sup>a</sup>	11.9 <sup>a</sup>
Maize 2 plants per hill	5.0 <sup>a</sup>	1.5 <sup>ab</sup>	2.7 <sup>b</sup>	4.7 <sup>bc</sup>
Mbili-Mbili	5.0 <sup>a</sup>	1.6 <sup>ab</sup>	2.9 <sup>b</sup>	6.9 <sup>b</sup>
Meru 513	5.5 <sup>a</sup>	1.6 <sup>ab</sup>	3.1 <sup>b</sup>	4.7 <sup>bc</sup>
Farmer Practice <sup>€</sup>	-	-	4.8 <sup>ab</sup>	2.5 <sup>c</sup>
<i>P-Value</i>	<i>0.229</i>	<i>0.045</i>	<i>0.001</i>	<i>0.001</i>
<i>LSD</i>	<i>1.468</i>	<i>0.486</i>	<i>1.506</i>	<i>1.504</i>

<sup>‡</sup>Treatments were consecutively rotated during the four seasons under test. <sup>€</sup>Treatment introduced in the 2020 and 2021 season. Values in same column followed by different letters are significantly different.

Pigeon pea grain and haulm yield had a positive and significant relationship with maize de-toppings and strippings during the 2019 and 2020 seasons (Figure 4.2). Each ton of maize

toppings and strippings resulted in a 15.4% and 94.3% increase in pigeon pea grain and haulm yield. However, increasing maize toppings/strippings beyond 2.0 t ha<sup>-1</sup> resulted in a corresponding diminishing return on both the grain and haulm yield.

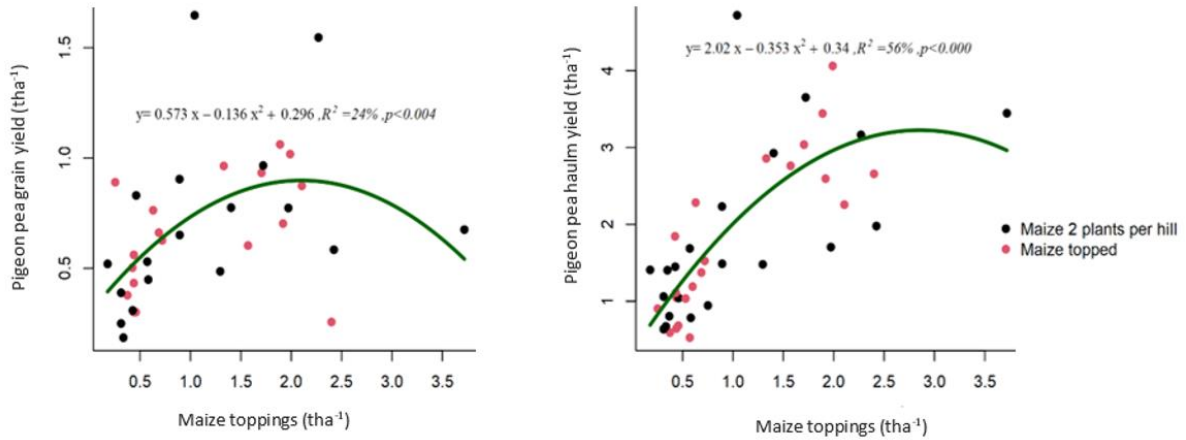


Figure 4.2. Influence of maize de-topping on grain and haulm yield of intercropped pigeon pea

Bean yield was as low as 0.12 t ha<sup>-1</sup> in 2018 upto 0.48 t ha<sup>-1</sup> in the 2021 season under Mbili-Mbili and 0.46 t ha<sup>-1</sup> in the 2019 to 1.28 t ha<sup>-1</sup> in 2020 season under doubled-up legume (Figure 4.3). Bean yield under doubled-up legume were 1.5 to 4 times higher for the haulms and 2 to 6 times higher for the grain component than the Mbili-Mbili system.

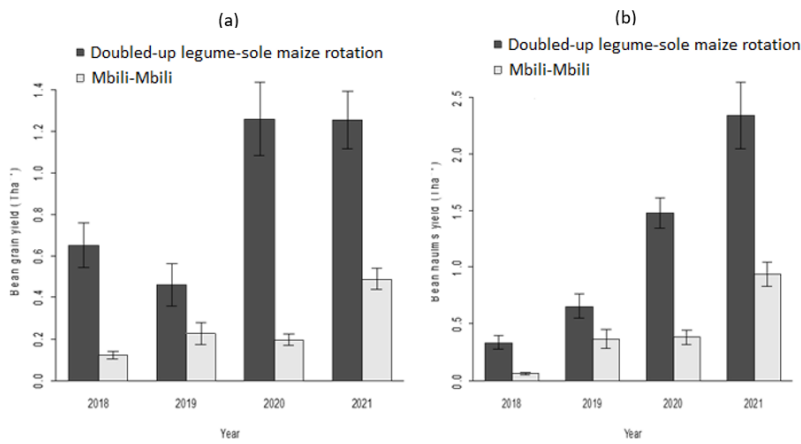


Figure 4.3. Yields attained from bean grain (a) and that of haulm components (b) between the 2018 and 2021 seasons in Babati, Tanzania. Error bars represent 95% confidence intervals while pair-wise error bars in same year that are not crossing are significantly different.

Higher bean and pigeon pea yields were recorded under doubled-up legume relative to that of maize-based systems. The slow growth of pigeon pea complemented the rapid growth of beans under doubled-up legume resulting in dismal competition for growth resources. Interestingly, the system accommodated a second bean phase which also reached podding stage before pigeon pea developed a dense canopy. The second bean phase was identified as an important additive to the improvement of the system's economics. The competitive advantage of maize due to ISFM targeting coupled with the low population of bean plant might be the reason why Mbili-Mbili system had reduced bean yield than doubled-up legume. This agrees with findings on interspecific competition for growth resources under improved 1:1 and 1:2 maize-legume intercrops that has been associated with the low yields of intercropped legumes (Myaka *et al.*, 2006; Kimaro *et al.*, 2009; Madembo *et al.*, 2020). Doubled-up legume was also identified as having potential to produce beans of upto 1.3 t ha<sup>-1</sup>, in a good season, which is greater than the 0.3-0.5 t ha<sup>-1</sup> documented under conventional systems of the study area (Mligo and Craufurd, 2004; Hillocks *et al.*, 2006). Mbili-Mbili and doubled-up legume does not only increase productivity of associated crops but also improves nutrition security, food diversity (Phiri *et al.*, 2012) and soil health benefits i.e., upto 92 kg N ha<sup>-1</sup> of biologically fixed nitrogen (Mhango *et al.*, 2011, 2017), upto 2.4 t ha<sup>-1</sup> of bean haulm for forage and 12 t ha<sup>-1</sup> of biomass fuel from pigeon pea stems (Kinyua *et al.*, 2023).

Pigeon pea yield under the farmer practice was higher, in some seasons, than that of improved maize-pigeon pea systems which could be attributed to sub-optimal maize population. The low plant population resulting from farmers broadcasting seeds behind animal and/or tractor ploughs and the poor spacing of maize allows for more solar radiation interception, moisture, and nutrient access by pigeon pea improving its growth. The high proliferation of maize under improved maize-pigeon pea systems has been reported to suppress pigeon pea haulm and grain yields by 60% and 30%, respectively, with the legume failing to recover from effects of interspecific competition after maize is harvested (Kimaro *et al.*, 2009). Associating penalty in pigeon pea yield with the high maize population agrees with findings by Mugi-Ngenga *et al.* (2021) who reported an average maize population of 26,000 plants under farmer practices relative to 53333 plants per ha<sup>-1</sup> achieved under improved practices. This might have caused a solar radiation access challenge by the intercropped legume. While Mbili-Mbili allows crop diversification through integration of bean and pigeon pea in maize-based systems (Kinyua *et*

*al.*, 2023), doubled-up legumes can be utilized as a crop diversification strategy for optimizing yield of pure legume systems (Chikowo *et al.*, 2020). This would not only increase agricultural economics but also promote soil health while enhancing climate resilience of smallholder farming systems as indicated by Snapp and Fisher (2015).

De-topping and stripping of maize provided early light penetration to the intercropped legumes and was associated with improved pigeon pea bloom. Although pigeon pea yields were not affected by de-topping during this and other studies (Mashingaidze, 2004), a positive relationship between de-topping of maize and increased pigeon pea biomass was established. Other studies have also observed higher biomass and grain yields of legumes and other crop species following stripping and de-topping. For example, Mañgaser (2013) reported a land equivalent ratio of 1.15 when maize intercropped with okra was de-topped relative to land equivalent ratio of 1.04 in similar system without de-topping.

#### ***4.3.3 Maize Equivalent Yield***

Maize equivalent yields were significantly affected by treatments and the cropping seasons. Averaged across the cropping seasons, the 2020 (6.1 t ha<sup>-1</sup>) and 2021 (8.2 t ha<sup>-1</sup>) cropping seasons had significantly higher maize equivalent yield than the 2018 (2.4 t ha<sup>-1</sup>) and 2019 (1.9 t ha<sup>-1</sup>) seasons ( $P \leq 0.05$ ; Table 4.4). The legume-based doubled-up legume treatment had consistently lower maize equivalent yield than the cereal-based treatments, except for the farmer practice. However, significantly higher maize equivalent yield in doubled-up legume than cereal-based treatments (except Mbili-Mbili) were observed during the 2021 season. Mbili-Mbili had a consistently high maize equivalent yield across the cropping seasons.

Table 4.4. Effect of cropping systems on maize equivalent yield (t ha<sup>-1</sup>) during four cropping seasons in Babati, Tanzania

Treatments	Maize equivalent yields (t ha <sup>-1</sup> )			
	2018	2019	2020	2021
Sole maize	2.4 <sup>a</sup>	2.0 <sup>a</sup>	6.2 <sup>a</sup>	5.5 <sup>c</sup>
Maize no-topping	2.8 <sup>a</sup>	2.0 <sup>a</sup>	5.9 <sup>a</sup>	6.5 <sup>bc</sup>
Maize topped	2.5 <sup>a</sup>	1.9 <sup>ab</sup>	6.5 <sup>a</sup>	7.3 <sup>bc</sup>
Doubled-up legume	1.0 <sup>b</sup>	1.2 <sup>b</sup>	4.3 <sup>b</sup>	12.2 <sup>a</sup>
Maize 2 plants per hill	2.6 <sup>a</sup>	1.7 <sup>ab</sup>	6.1 <sup>a</sup>	7.9 <sup>b</sup>
Mbili-Mbili	2.4 <sup>a</sup>	2.4 <sup>a</sup>	6.7 <sup>a</sup>	10.3 <sup>a</sup>
Meru 513	2.8 <sup>a</sup>	2.1 <sup>a</sup>	6.7 <sup>a</sup>	7.5 <sup>b</sup>
Farmer practice <sup>€</sup>	-	-	3.0 <sup>c</sup>	6.0 <sup>bc</sup>
<i>LSD</i>	0.49	0.74	1.25	2.02
<i>P-values</i>	0.001	0.05	0.001	0.001

<sup>€</sup> Treatment assessed only in the 2020 and 2021 cropping season. Values within the same column and followed with different letters are significantly different.

Manipulating plant spatial patterns increased maize equivalent yield of Mbili-Mbili despite the system having multiple plant components per unit area. The increased maize equivalent yield under Mbili-Mbili can be attributed to reduced interspecific competition for growth resources which might have enhanced yields of the two legume species, while posing minimal effects on productivity of maize. The similar pigeon pea yields as other maize-pigeon pea systems cushioned Mbili-Mbili from yield penalty, while the high market prices of beans made this system as well as doubled-up legume to break even in 2021 season. The biological efficiency of Mbili-Mbili intercropping, coupled with its higher land equivalent ratio than the common maize-pigeon pea intercropping, assures benefits to the vulnerable and land constrained smallholder farmers. Similar benefits accrued from cropping system diversification through integration of cereals with profitable legume crops were reported by Syafruddin (2020) with intercropping having higher maize equivalent yields of between 7.2 – 9.7 t ha<sup>-1</sup> above 6.0 t ha<sup>-1</sup> in maize and 6.4 t ha<sup>-1</sup> in legume monoculture. The higher yield equivalences attained following crop diversification with high value crops makes more diverse intercropping systems such as Mbili-Mbili to have stable net revenues relative to

monoculture systems (Exner *et al.*, 1999). Besides crop diversification, Ghosh *et al.* (2004) indicated the need for applying other ISFM aspects such as fertilizers and organic manure to increase yield equivalence of the unfertilized farmer systems such as those of the study area.

The high maize equivalent yield of doubled-up legume in the 2021 season relative to that of other maize-based systems was interesting to compare with low maize equivalent yield of the same system in previous seasons. This can be used as an indicator of instability of doubled-up legume to changes in seasonal weather. For example, a farmer can obtain low proceeds in a poor rainfall season (2019) but reap high benefits in a good (2021) season. In addition, maize equivalent yields under doubled-up legume more than doubled that of sole maize system indicates potential benefits that can be accrued if the two systems are backed by an accurate climate information system. The yield gains in doubled-up legume relative to sole maize system agrees with Syafruddin (2020) on grain yield of upto 3.7 t ha<sup>-1</sup> increase in intercrops against sole crops. Moreover, variability in maize equivalent yields under doubled-up legume – sole maize rotation resonates with the proposed support on climate information service relating to suitability of cropping systems for specific seasons (Antwi-Agyei *et al.*, 2021).

#### ***4.3.4 Effects of Treatments on Benefit Cost Ratio and Value Cost Ratio***

Net revenue, benefit to cost ratio and value to cost ratio were significantly affected by cropping seasons and ranged from US\$ -161 in 2018 to US\$ 1438 in 2021 (Table 4.5). The doubled-up legume treatment had the lowest net revenues in the 2018 and 2019 seasons despite having the highest in 2021. Mbili-Mbili had high net revenues in the 2019 season, that were significantly higher than Maize 2 plants per hill and sole maize treatments and in the 2020 season, significantly higher than Meru 513 and the farmer practice ( $P \leq 0.05$ ). Like doubled-up legume, Mbili-Mbili also had significantly higher net revenues in 2021 relative to other practices. Sole maize system had significantly lower total variable production costs i.e., US\$ 100 to 250, than other treatments, however, farmer practice had US\$ 80-120 less operational cost than the doubled-up legume rotational systems. Mbili-Mbili had significantly lower total variable cost than the maize-pigeon pea system with no de-topping despite the integration of more intercropping components. Mbili-Mbili was 21% and 55% more costly to plant despite being 49% and 57% cheaper to weed relative to Maize no de-topping and doubled-up legume, respectively. While all treatments had a benefit cost ratio  $>1$  in the 2020

season, only doubled-up legume, Mbili-Mbili and farmer practice attained the profitable benefit cost ratio  $\geq 1$  in the 2021 season (Table 4.5).

Table 4.5. Annual net benefits (US\$), benefit to cost ratio and value to cost ratio from the treatments implemented in Babati, Northern Tanzania between the 2018 and 2021 cropping seasons

Treatment	NP	BCR	VCR	NP	BCR	VCR	NP	BCR	VCR	NP	BCR	VCR
	2018			2019			2020			2021		
Sole maize	-47 <sup>a</sup>	-0.1 <sup>a</sup>	2.0 <sup>a</sup>	37 <sup>c</sup>	0.7 <sup>ab</sup>	3.7 <sup>a</sup>	1,112 <sup>a</sup>	1.7 <sup>abc</sup>	5.5 <sup>a</sup>	1438 <sup>a</sup>	0.4 <sup>d</sup>	4.4 <sup>c</sup>
Maize no de-topping	-16 <sup>a</sup>	-0.0 <sup>a</sup>	2.4 <sup>a</sup>	291 <sup>abc</sup>	0.5 <sup>abc</sup>	3.8 <sup>a</sup>	994 <sup>a</sup>	1.4 <sup>bc</sup>	5.3 <sup>a</sup>	368 <sup>cd</sup>	0.5 <sup>cd</sup>	5.2 <sup>bc</sup>
Maize de-topped	-99 <sup>ab</sup>	-0.2 <sup>a</sup>	2.1 <sup>a</sup>	207 <sup>abc</sup>	0.4 <sup>bcd</sup>	3.5 <sup>a</sup>	1,156 <sup>a</sup>	1.4 <sup>bc</sup>	5.5 <sup>a</sup>	499 <sup>cd</sup>	0.7 <sup>cd</sup>	5.9 <sup>b</sup>
Doubled-up legume	-161 <sup>b</sup>	-0.4 <sup>b</sup>	-	343 <sup>ab</sup>	0.1 <sup>d</sup>	-	992 <sup>a</sup>	2.0 <sup>a</sup>	-	269 <sup>d</sup>	2.5 <sup>a</sup>	-
Maize 2 plants per hill	-80 <sup>ab</sup>	-0.1 <sup>a</sup>	2.2 <sup>a</sup>	141 <sup>bc</sup>	0.2 <sup>cd</sup>	3.1 <sup>a</sup>	970 <sup>a</sup>	1.3 <sup>bc</sup>	5.2 <sup>a</sup>	578 <sup>c</sup>	0.8 <sup>c</sup>	6.3 <sup>b</sup>
Mbili-Mbili	-70 <sup>ab</sup>	-0.1 <sup>a</sup>	2.0 <sup>a</sup>	418 <sup>a</sup>	0.8 <sup>a</sup>	4.2 <sup>a</sup>	1,200 <sup>a</sup>	1.7 <sup>ab</sup>	5.9 <sup>a</sup>	987 <sup>b</sup>	1.3 <sup>b</sup>	8.1 <sup>a</sup>
Meru 513	-17 <sup>a</sup>	-0.0 <sup>a</sup>	2.4 <sup>a</sup>	320 <sup>ab</sup>	0.6 <sup>abc</sup>	3.9 <sup>a</sup>	1,108 <sup>a</sup>	1.5 <sup>abc</sup>	5.7 <sup>a</sup>	520 <sup>cd</sup>	0.7 <sup>cd</sup>	5.9 <sup>b</sup>
Farmer Practice <sup>€</sup>	-	-	-	-	-	-	413 <sup>b</sup>	1.3 <sup>c</sup>	-	524 <sup>cd</sup>	1.2 <sup>b</sup>	-
<b><i>P-value</i></b>	<i>0.034</i>	<i>0.001</i>	<i>0.091</i>	<i>0.05</i>	<i>0.008</i>	<i>0.372</i>	<i>0.003</i>	<i>0.047</i>	<i>0.513</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>
<b><i>LSD</i></b>	<i>92.2</i>	<i>0.16</i>	<i>0.36</i>	<i>273.5</i>	<i>0.38</i>	<i>0.99</i>	<i>434.2</i>	<i>0.44</i>	<i>0.72</i>	<i>301.0</i>	<i>0.34</i>	<i>0.82</i>

<sup>€</sup> Treatment assessed only in the 2020 and 2021 cropping season. NP represents net profitability, BCR is benefit to cost ratio and VCR is value to cost ratio. Values within the same column and followed with different letters are significantly different.

Doubled-up legume had the lowest benefit to cost ratio in 2018 and 2019 and consecutively the highest in the 2020 and 2021 seasons. For the cereal-based systems, Mbili-Mbili system had the highest benefit to cost ratio between the 2019 and 2021 seasons relative to the other maize-pigeon pea systems. Effect of treatments on value cost ratio was visible in the 2021 season and not in the rest of the seasons (Table 4.5). In the 2021 season, Mbili-Mbili system had a value to cost ratio of 8.1 which was not only significantly higher than the rest of the treatments but the highest across the four seasons of study. All treatments had a value to cost ratio  $>2$  in entire seasons of study.

Across the trial period, a unit of investment in fertilizer in the improved maize-legume systems resulted in a positive return on investment that was economically viable, considering all treatments had a value cost ratio  $>2$ . This indicates that utilizing N and P fertilizers is a profitable investment for smallholder farming systems of the study area, considering the two nutrients were found to be deficient in soils of the different sites. Exposure of farmer fields to continuous crop production coupled with poor management practices such as low use of fertilizers to replace mined nutrients results in maize yield response to fertilizer application. The value cost ratio  $>2$  has been documented by Kihara *et al.* (2015b) as a profitable threshold for use of fertilizers. Indeed, studies by Kihara *et al.* (2021) recommended judicious use of fertilizer rates of 50 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup> as profitable and sustainable for maize-based systems of Babati. Elsewhere in Babati, Mugi-Ngenga *et al.* (2022a) indicated 90 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup> while Kinyua *et al.* (2021) documented 80 kg N ha<sup>-1</sup> and 60 kg P ha<sup>-1</sup> as profitable for maize production in Central highlands of Kenya. This indicates that fertilizers should not be blanket applied but rather site-specific for farmer fields in similar or different agro-ecological conditions of SSA (MacCarthy *et al.*, 2018).

Mbili-Mbili had the highest return on investment in 3 of 4 seasons and a maximum value cost ratio of upto 8.1 relative to 6.3 in other treatments which indicates that profitability of the system is strongly embedded on both its richness in crop diversity and application of inorganic fertilizer. In addition, Mbili-Mbili had two seasons when the benefit cost ratio was  $>1$  compared to the rest of improved cereal-legume systems with only one season which indicates higher chances of farmers evading weather associated losses if they adopt this system. This agrees with our previous finding where Mbili-Mbili recorded higher maize equivalent yields than the rest of cereal-based systems which is another indicator of stability of the system against weather associated shocks. Results of this study sensitizes farmers on the need of integrating ISFM practices such as inorganic fertilizers

(Vanlauwe *et al.*, 2011; Kinyua *et al.*, 2021), manure (Mucheru-Muna *et al.*, 2014; Ejigu *et al.*, 2021), adopting crop diversification (Snapp and Fisher, 2015) and using improved seed varieties (Vanlauwe *et al.*, 2019) to ensure their systems are sustainable and climate resilient.

The amount of labor associated with a cropping system had a great bearing on its profitability. Planting seeds behind the plough and evading fertilizer associated costs resulted in farmer practice incurring lower total variable cost hence a corresponding higher benefit cost ratio than majority of improved practices in 2021. In addition, Mbili-Mbili is labor intensive and costly to plant but had higher benefit cost ratio which was not only attributed to crop diversification but also cheaper weeding cost than other improved practices (Kinyua *et al.*, 2023). Indeed, sole systems have been reported to have a reduced cost and intensity of labor (Rusinamhodzi *et al.*, 2012). However, these systems have low benefit to cost ratio (Sun *et al.*, 2021) and value to cost ratio as was observed in the 2021 season. Sole maize system can produce higher maize yield due to lesser intraspecific competition, but the total value of the system could be much lower compared to that of intercropped systems (Madembo *et al.*, 2020). The system has higher weather associated risks and negative influence on soil health which makes it to be unsustainable agronomic investment (Rusinamhodzi *et al.*, 2012).

#### ***4.3.5 Stability of the Different Treatments Across Study Period***

Stability analyses was based on Shukla variance and indicated sole maize and doubled-up legume rotations having both the highest overall mean net revenue (\$653) and variance (16), depending on the starting phase (Table 4.6). Mbili-Mbili had the second highest overall mean net revenue (\$623) and a lower variance. Improved maize-pigeon pea system with de-topped maize and Mbili-Mbili were the most stable systems. Mbili-Mbili had at least US\$ 220 higher net revenue than maize-pigeon pea system with de-topping, hence the best-bet technology in terms of profitability and stability across the variable seasonal weather.

Table 4.6. Stability of overall revenue for treatments implemented in Babati between the 2018 and 2021 seasons

Treatment	Mean net revenue (US\$)	Shukla Variance	Rank of Revenue	Rank of Variance	Sum of rank of revenue and variance
Sole maize <sup>‡</sup>	653 <sup>a</sup>	52565	1	7	8
Maize no topping	379 <sup>b</sup>	-2148	7	1	8
Maize de-topped	396 <sup>b</sup>	-1406	5	2	7
Doubled-up legume <sup>‡</sup>	326 <sup>b</sup>	103850	8	8	16
Maize 2 plants per hill	384 <sup>b</sup>	-1224	6	3	9
Mbili-Mbili	623 <sup>a</sup>	1338	2	5	7
Meru 513	454 <sup>ab</sup>	650	4	4	8
Farmer Practice*	468 <sup>ab</sup>	1609	3	6	9
<i>P-value</i>	<i>0.01</i>				
<i>LSD</i>	<i>202.4</i>				

<sup>‡</sup>Treatments consecutively rotated for a period of four seasons. \*Treatment assessed for only 2 cropping seasons therefore not considered in the discussions of treatment stability. Values in same column followed by different letters are significantly different.

Although doubled-up legume had very high net revenue in some years, it had a large variance which indicates its implementation is associated with high risk. The risk is attributed to presence of beans, which are more vulnerable to extreme weather conditions (dry spell or moisture saturation) hence probability of incurring losses. On the other hand, it may perform extremely well in a season with well distributed rainfall resulting in high revenue generation. Nevertheless, the system allows for two bean phases which if harnessed can help to reduce the weather associated risk. Similar results of lower profitability of doubled-up legume relative to maize-legume systems was reported in multilocational studies conducted in Malawi by Snapp *et al.* (2018). In addition, Mwila *et al.* (2021) reported doubled-up legume as having higher land equivalent ratios than sole legume systems, but performance differed in different seasons indicating instability of the system across different weather. This could be the reason Steward *et al.* (2018) recommended for development of crop management system that are more resilient and adapted to changing climate.

Otherwise, recommendations by Kinyua *et al.* (2023) on integrating climate information services to farmer operations to guide on when such systems with low labor demands and potential for high revenue generation, but vulnerable to seasonal weather, can be implemented.

A sole maize system planted in the season following doubled-up legume also had low revenue which made the whole rotational system unattractive to farmers. Like the previous profitability indicators, results from stability analysis also indicate that success of rotational system involving doubled-up legume and sole maize would depend on farmers' ability to target the two systems to appropriate seasonal weather. High and moderately stable (low variances) net revenues with Mbili-Mbili system are attributed to the sustained high productivity of cereal and modest yields of the two intercropped legumes (pigeon pea and common beans). Results from this study demonstrate the value of increased crop diversity, associated with increased food security (Snapp and Fisher, 2015; Li *et al.*, 2009), food availability due to staggered harvests, and reduced risk of crop failure (Makate *et al.*, 2016). Indeed, similar results were reported in Kenya where MBILI, a legume diversified system proved to be more profitable than conventional maize-legume intercrops, when tested across scale (Mucheru-Muna *et al.*, 2010).

#### *Hypothesis testing*

**H<sub>0</sub>:** Improved cropping systems do not increase the economics of conventional cereal-legume intercropping systems.

Findings of this study reject the null hypothesis. Indeed, improved cropping systems like Mbili-Mbili and Doubled-up legume can increase the economic returns by between US\$ 200-250 over that of conventional maize-pigeon pea intercropping. This suggests that farmers could benefit economically from transitioning to improved cropping systems under similar conditions. Though having same average economic benefits as sole maize system, Mbili-Mbili is more stable to seasonal weather changes hence boosting farmer's resilience to climate change than the former.

## **4.4 Effect of Different Cropping Systems on Biological Nitrogen Fixation Capacity of Intercropped Legumes**

### ***4.4.1 Effect on N-fixation***

Biological nitrogen fixation was significantly affected by both sites and seasons and not by treatments. Gallapo village had significantly higher N fixation levels (M = 76.5, 65.0 and 88.7 kg;

SD = 29.7, 28.7 and 39.2) than Sabilo (M = 48, 34.0 and 43.5 kg; SD = 14.6, 21.7 and 15.2), with an average difference of 27.8, 31.0 and 45.3 kg ( $P \leq 0.047, 0.001$  and  $0.001$ ) during the 2019, 2020 and 2021 seasons, respectively. Averaged across treatments, the amount of N fixed was in the order of  $2021 \geq 2019 \geq 2020$  season with 67.8, 58.5 and 49.2 kg of N, respectively ( $p \leq 0.028$ ). The amount of N fixed in the pigeon pea haulms ( $51.4 \text{ kg ha}^{-1}$ ) was more than that of the roots ( $5.7 \text{ kg ha}^{-1}$ ) at mid-podding stage and grain component ( $2.6 \text{ kg ha}^{-1}$ ) during harvest (Table 4.7). An average of 3.5 kg of the N fixed under maize-pigeon pea intercropping was removed through the harvested pigeon pea grain (2.8 kg) and the husks (0.9 kg) generated after threshing pigeon pea pods. Under Mbili-Mbili and doubled-up legume systems, an addition of 11.4, 3.6 and 0.9 kg is also lost from crop fields by removal through bean grain, bean haulms, and husks, respectively. Farmer practice had inconsistent N fixation levels with relatively higher and sometimes the lowest  $^{15}\text{N}$  in some seasons and sites. For example, In the 2019 season, farmer practice in Sabilo village fixed  $>37 \text{ kg}$  ( $p \leq 0.01$ ) than all improved practices, except doubled-up legume and maize-pigeon pea system with no de-topping. In 2020, doubled-up legume had higher N fixed in the pigeon pea litter than that of maize-pigeon pea intercrop with no de-topping, Maize (2 plants per hill) and Meru (H513) intercropped with pigeon pea.

Table 4.7 Treatment effects on biological nitrogen fixation of different legume components during the 2019-2021 seasons in Babati, Tanzania

Treatment	Gallapo			Sabilo				
	Haulms	Roots	Total N fixed	Haulms	Roots	Total N fixed		
	2019			2020				
Sole maize	-	-	-	-	-	-		
Maize no topping	63.4	16.8	2.1	0.62	80.1	42.2 <sup>ab</sup>	6.2 <sup>ab</sup>	64.7 <sup>ab</sup>
Maize de-topped	58	10.5	2.8	0.9	68.5	27.2 <sup>ab</sup>	4.6 <sup>b</sup>	37.3 <sup>b</sup>
Doubled-up legume	35.3	5.6	3.2	1.2	40.9	37.4 <sup>ab</sup>	5.6 <sup>ab</sup>	43.0 <sup>b</sup>
Maize 2 plants per hill	58.4	5.7	2.3	0.6	81.4	35.4 <sup>ab</sup>	4.7 <sup>b</sup>	40.1 <sup>b</sup>
Mbili-Mbili	40.7	4.5	2.6	0.8	45.2	22.2 <sup>b</sup>	5.0 <sup>b</sup>	36.8 <sup>b</sup>
Meru 513	60.6	7	2.7	1.3	67.6	33.8 <sup>ab</sup>	5.0 <sup>b</sup>	38.8 <sup>b</sup>
Farmer Practice	85.8	8.8	2.6	0.9	94.6	64.97 <sup>a</sup>	9.1 <sup>a</sup>	74.1 <sup>a</sup>
<i>p-value</i>	0.381	0.34	0.97	0.699	0.175	0.045	0.017	0.006
<i>LSD</i>	46.8	11.5	2.8	1.2	44.5	24	2.4	18.7
					2020			
Sole maize	-	-	-	-	92.0	-	-	-
Maize no topping	83.8 (3.3 <sup>b</sup> )	8.1			71.1	35.9 (11.3)	5.9	41.8
Maize de-topped	66.2 (6.4 <sup>ab</sup> )	6.9			15.9 (8.1)	4.7		20.6
Doubled-up legume	83.8 (29.5 <sup>a</sup> )	11			95.0	24.2 (29.7)	3.9	28.1
Maize 2 plants per hill	48.1 (4.3 <sup>b</sup> )	4.9			53.0	27.9 (8.4)	6.6	34.4
Mbili-Mbili	58.5 (9.3 <sup>ab</sup> )	5.7			64.2	19.4 (7.9)	3.6	23.1
Meru 513	53.8 (4.4 <sup>b</sup> )	5.4			59.2	26.4 (8.1)	7.1	33.6
Farmer Practice	28.2 (10.0 <sup>ab</sup> )	4.2			32.4	49.7 (18.1)	6.8	56.5
<i>p-value</i>	0.164 (0.025)	0.152			0.148	0.406 (0.276)	0.66	0.458
<i>LSD</i>	44.6 (14.6)	5.1			48.0	32.9 (21.0)	5.4	37.4
					2021			
Sole maize	-	-	-	-	-	-	-	-
Maize no topping	85.2	4.1			89.3	39.7	2.3	42.1

Maize de-topped	76.3	5.2	81.5	46.6	3.1	49.6
Doubled-up legume	115.1	5.6	120.7	41.3	3.7	45
Maize 2 plants per hill	72.2	4.6	76.7	31.9	1.8	33.7
Mbili-Mbili	85.6	6.1	91.7	44.4	1.8	45.6
Meru 513	110.6	4.7	115.3	42.2	2.7	44.8
Farmer Practice	43.4	2.4	45.8	41	2.6	43.5
<i>p-value</i>	0.287	0.543	0.298	0.929	0.236	0.923
<i>LSD</i>	62.9	4.2	65.9	31.8	1.9	32.9

*Values in same column followed by different letters are significantly different. Values in parenthesis are means for the total N fixed in leaf litter abscised by pigeon pea*

Utilizing same variety of legume species under variable treatments had a weak influence on variation in the quantity of N fixed. Cultivation of sole legume system (doubled-up legume) did not significantly influence the overall N fixed when compared to systems with cereal-legume intercrops. However, this study established that the sole legume system had higher N turnover of pigeon pea litter fall than maize-pigeon pea intercrops. The higher  $^{15}\text{N}$  levels attained from leaf litter fall under doubled-up legume could be due to higher quantities of abscised leaf biomass relative to those recorded in maize-pigeon pea intercropping. Results of this study on similar levels of N fixation being recorded in pure legume and intercropped systems contradicted those of Mhango *et al.* (2017) where the former doubled the fixation levels of the latter. Findings from this study agree with Mugi-Ngenga *et al.* (2022b) who observed significant differences in N fixation across two pigeon pea genotypes but not under variable cropping systems with same genotype. In addition, Myaka *et al.* (2006) and Egbe *et al.* (2007) indicated that fixation of N by pigeon pea is influenced by the genotype planted and the prevailing environmental conditions. Pure legume systems have also been reported as generating between 41-57% more leaf biomass than those intercropped with cereal crops a phenomenon attributed to interspecific competition by the cereal companion (Baldé *et al.*, 2011; Mhango *et al.*, 2017).

The quantity of N fixed differed for different species of legumes planted during this study. Integrating pigeon pea under maize-based systems offered higher soil N gains than the intercropped beans. This study established that up to  $16 \text{ kg N ha}^{-1}$  fixed by beans ended up being removed through the grain, in addition to haulms and husks that are harvested for use as livestock fodder. The nutrient exports from crop fields decrease the likelihood of beans having a significant contribution to soil fertility improvement, less for the little benefit of few decomposed nodules, residual roots, and abscised leaves. Contrary, pigeon pea produces large quantities of leaf litter, roots and nodules which are later incorporated in the soil after crop harvest. Ncube *et al.* (2009) indicated pigeon pea litter fall to be an important contributor of soil fertility improvement than retaining the haulms. Indeed, residual pigeon pea roots and leaf litter retained in crop fields conserve up to one-third of the total  $^{15}\text{N}$  fixed by pigeon pea (Peoples *et al.*, 2009; 2021) which significantly improves the yield of subsequent cereal crop. However, while legumes have been promoted as an alternative source of N, the low levels of N fixed by beans and post-harvest grazing that removes N-rich pigeon pea biomass makes the sole use of legume-based systems (without ISFM) to be unsustainable for supporting maize production (Mhango *et al.*, 2017).

The differences in N fixation rates observed between sites could be attributed to variation in the nutrient levels of the soil. The higher P and Zn content in Gallapo (i.e., 72.8 ppm and 15.4 ppm, respectively) than Sabilo village (21.7 ppm and 1.4 ppm) could be the major reason for enhanced N fixation levels in the former than the latter site. In addition, Sabilo had slightly lower pH which might have negatively impacted the activity of nitrogen fixing microbial group in the soil. Biological nitrogen fixation can be utilized as a cheaper N alternative for smallholder farmer systems (Yakubu *et al.*, 2010a) especially during the current period when fertilizer prices are higher than many resource-poor farmers can afford (Mebrate and Kippie, 2023). However, there is a need to ensure that soils are well managed to be able to provide minimum nutrient requirements or are boosted with sufficient levels of nutrients to activate and promote optimal N fixation (Zhong *et al.*, 2023). The output of this study was consistent with Weisany *et al.* (2013) that improving soil available P can encourage root development, which acts as sites for nodule formation while Zn improves biomass production thus promoting N fixation process. In addition, increased soil acidity, as was the case with Sabilo, can cause detrimental effects on the survival and persistence of rhizobium bacteria which are key for N fixation (Hungria and Vargas, 2000).

#### ***4.4.2 Pigeon pea Litter Fall***

Pigeon pea litter fall was significantly influenced by sites and treatments ( $p \leq 0.05$ ). Averaged across the treatments, pigeon pea litter yield was in the order of Sabilo > Riroda  $\geq$  Gallapo with 0.8, 0.56 and 0.52 t ha<sup>-1</sup> of senesced leaves, respectively. Both the doubled-up legume and the farmer practice had significantly higher dry matter yield than the rest of the cropping systems (Figure 4.4).

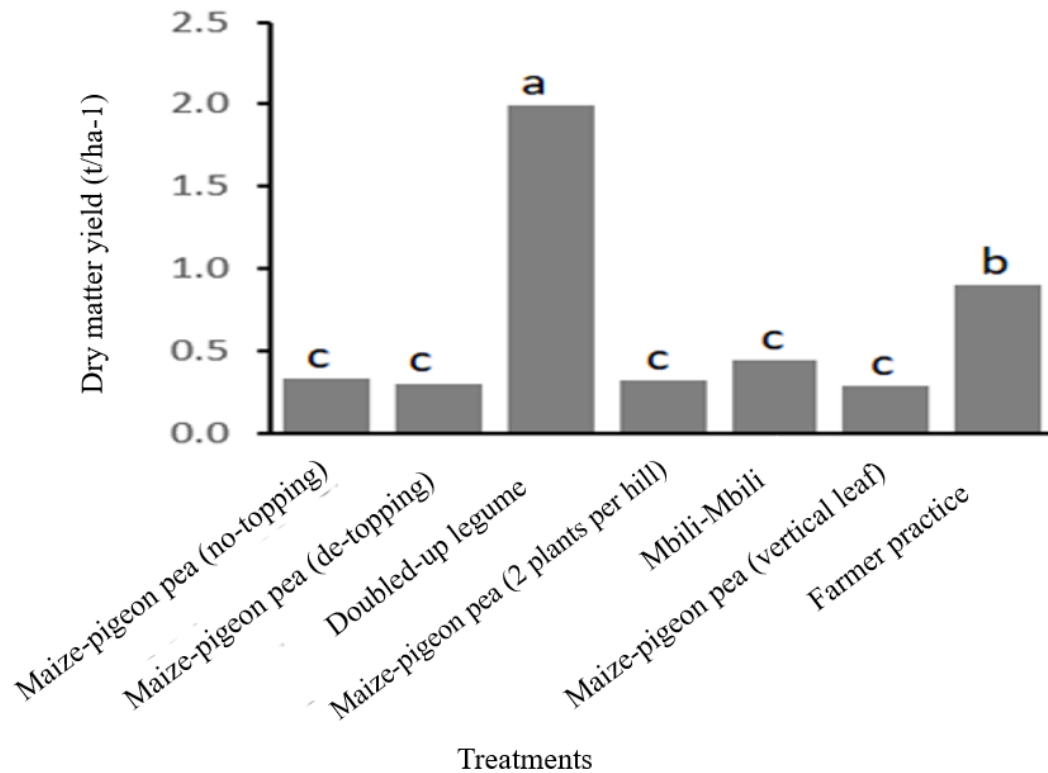


Figure 4.4. Cumulative dry matter yield from abscised pigeon pea leaves during the 2020 season in Babati. PP represents pigeon pea.

The amount of biomass accumulated by pigeon pea crop in the different cropping systems had a strong positive effect on the amount of litter abscised by the crop. The absence of maize and minimal interspecific competition effects from intercropped beans in doubled-up legume system might have contributed to proliferation of pigeon pea crop resulting in increased leaf dry matter yield during this study. In addition, the temporal niche complementarity (Mugi-Ngenga *et al.*, 2022a), was more pronounced in doubled-up legume than in maize-pigeon pea intercrops thus reducing competition for growth resources in the former than the latter systems. The problem of interspecific competition among intercropping companions is not limited to Babati but resulted in 57% lower pigeon pea litter under intercropped than sole legume systems in Malawi (Mhango *et al.*, 2017). Indeed, this forms the major reason why studies (Kimaro *et al.*, 2009; Stewart *et al.*, 2018; Madembo *et al.*, 2020) recommended for crop management systems that would offer spatial niche complementarity for optimal yield and soil health benefits from cereal-legume systems.

The low levels of soil fertility and inorganic fertilizer use (in <15% of fields), average utilization of manure that is low in quality and crops poorly spaced in farmer practices of Babati could have contributed to higher N fixed by pigeon pea in some seasons and sites relative to the improved practices. The above-mentioned challenges have pronounced (negative) effects on maize productivity but favors proliferation of the intercropped pigeon pea under farmer practices. For this reason, pigeon pea gets a competitive advantage to fix N, with its deep rooting system also helping to access leached nutrients from lower soil depth. This enhances the development of pigeon pea dry matter yield under farmer practices compared to improved maize-pigeon pea systems. Similar reason makes doubled-up legume to produce greater quantities of abscised leaves ( $2 \text{ t ha}^{-1}$ ) than improved maize-pigeon pea systems ( $0.4 \text{ t ha}^{-1}$ ), especially after intercropped maize is applied with inorganic fertilizers (Pierre *et al.*, 2022). The abscised leaves are important for enhancing soil organic matter (Amougou *et al.*, 2012) and fertility upon nutrient turnover by micro-fauna (Bathula *et al.*, 2023). Rotating doubled-up legume with cereal monoculture systems could enhance utilization of residual nutrients (Snapp *et al.*, 2018; Chikowo *et al.*, 2020) i.e., 75–95 kg N  $\text{ha}^{-1}$  from abscised pigeon pea dry matter (Sakala, 1994) in addition to other non-N effects.

#### ***4.4.3 Partial Factor of Production of Nitrogen and Phosphorus***

Partial factor of production was significantly affected by the season ( $P \leq 0.001$ ), site ( $P \leq 0.001$ ) and interaction between treatment, season, and site ( $P \leq 0.032$ ). However, it was not affected by treatment ( $P \leq 0.059$ ) as an individual factor. Despite being not significant, application of 50 kg N  $\text{ha}^{-1}$  resulted in maize grain yield increases of between 39.2 to 48.4 kg  $\text{ha}^{-1}$  in the 2018, 27.0 to 37.5 kg  $\text{ha}^{-1}$  in 2019, 105.6 to 123.9 kg  $\text{ha}^{-1}$  in 2020 and 76.3 to 105.5 kg  $\text{ha}^{-1}$  in 2021 seasons (Table 4.8). On the other hand, application of 20 kg P  $\text{ha}^{-1}$  resulted in maize grain yield increases of between 98.0 to 124.2 kg  $\text{ha}^{-1}$  in the 2018, 48.6 to 84.6 kg  $\text{ha}^{-1}$  in 2019, 259.1 to 309.5 kg  $\text{ha}^{-1}$  in 2020 and 183.2 to 262.2 kg  $\text{ha}^{-1}$  in 2021 seasons. Generally, application of P fertilizer resulted in a corresponding higher increase in maize grain yield than that of N.

Table 4.8. Partial factor of productivity of nitrogen and phosphorus fertilizer applied during the 2018-2021 seasons in Babati

Treatments	Partial factor of productivity							
	Nitrogen (50 kg ha <sup>-1</sup> )				Phosphorus (50 kg ha <sup>-1</sup> )			
	2018	2019	2020	2021	2018	2019	2020	2021
Sole maize	48.4 <sup>a</sup>	31.0 <sup>a</sup>	114.8 <sup>a</sup>	105.5 <sup>a</sup>	124.2 <sup>a</sup>	65.9 <sup>a</sup>	283.5 <sup>a</sup>	262.2 <sup>a</sup>
Maize no-topping	45.4 <sup>a</sup>	28.7 <sup>a</sup>	105.6 <sup>a</sup>	76.3 <sup>a</sup>	123.1 <sup>a</sup>	55.7 <sup>a</sup>	259.1 <sup>a</sup>	183.2 <sup>a</sup>
Maize topped	38.6 <sup>a</sup>	30.8 <sup>a</sup>	118.0 <sup>a</sup>	86.6 <sup>a</sup>	103.5 <sup>a</sup>	66.7 <sup>a</sup>	292.4 <sup>a</sup>	211.1 <sup>a</sup>
Doubled-up legume	-	-	-	-	-	-	-	-
Maize 2 plants per hill	39.2 <sup>a</sup>	32.0 <sup>a</sup>	112.8 <sup>a</sup>	87.5 <sup>a</sup>	98.0 <sup>a</sup>	75.3 <sup>a</sup>	281.6 <sup>a</sup>	219.4 <sup>a</sup>
Mbili-Mbili	42.0 <sup>a</sup>	27.0 <sup>a</sup>	114.0 <sup>a</sup>	89.5 <sup>a</sup>	119.8 <sup>a</sup>	48.6 <sup>a</sup>	279.6 <sup>a</sup>	210.8 <sup>a</sup>
Meru 513	43.5 <sup>a</sup>	35.7 <sup>a</sup>	123.9 <sup>a</sup>	90.0 <sup>a</sup>	108.3 <sup>a</sup>	84.6 <sup>a</sup>	309.5 <sup>a</sup>	226.1 <sup>a</sup>
Farmer practice	-	-	-	-	-	-	-	-
<i>LSD</i>	9.4	14.6	25.5	22.0	23.4	36.5	63.6	54.9
<i>P-values</i>	0.2	0.7	0.8	0.1	0.2	0.7	0.8	0.1

*Values of means in a column followed by different letters are significantly different*

Application of uniform rate of 50 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup> did not result in significant yield difference across treatments which implies that applying same rate of fertilizer would offer similar economic gains. Results from this study also indicate that farmers can experience slightly higher maize grain yield response if they invest in application of P fertilizer than they would do for N. This is because application of 50 kg N ha<sup>-1</sup> of Minjingu Topdressing fertilizer costing upto Tsh 280,000 resulted in maize grain yield valued at Tsh 123,800. On the contrary, application of 20 kg P ha<sup>-1</sup> of Minjingu Nafaka Plus fertilizer costing upto Tsh 120,000 resulted in maize grain increase of upto Tsh 312,000 which is more economically viable. The higher maize yield response to P fertilizer can be associated with the soils being Ferralsols, thus fixing soil available P (Bolo *et al.*, 2021), making it an important yield limiting nutrient in majority of smallholder fields in Babati (Kihara *et al.*, 2021). Introducing a fertilizer subsidy program that would aid farmers in accessing P fertilizer (Zakaria *et al.*, 2021), and an increased sensitization to improve its adoption by farmers (Okuma and Isiorhovoja, 2017) would be a significant intervention for unlocking crop yields in the smallholder systems. To reduce tradeoff on pigeonpea performance, broadcasting of seeds behind plough (Kizito *et al.*, 2021) can be complemented with cheap planter prototypes that are calibrated to ensure proper spacing (Ani *et al.*, 2016).

#### 4.4.4 Agronomic Efficiency of Nitrogen and Phosphorus Fertilizer

The agronomic efficiency of nitrogen and phosphorus fertilizer was significantly affected by site ( $P \leq 0.001$ ) for both the 2020 and 2021 seasons and treatments ( $P \leq 0.014$ ) only during the 2021 season (Table 4.9). The agronomic efficiency in the 2020 season was in the order of Sabilo  $\geq$  Gallapo  $\leq$  Riroda with  $87.3 \geq 49.7 \leq 46.5$  and  $218.3 \geq 124.2 \leq 116.2$  kg of maize grain for every kg of nitrogen and phosphorus, respectively. In the 2021 season, agronomic efficiency was in the order of Gallapo  $\geq$  Riroda  $\leq$  Sabilo with  $49.9 \geq 30.1 \leq 33.63$  and  $124.7 \geq 84.1 \leq 75.1$  kg of maize grain for every kg of nitrogen and phosphorus, respectively. Sole maize treatment had significantly higher agronomic efficiency in the 2020 (30.9 kg more) and 2021 (77.3 kg more) seasons than maize-pigeon pea without topping for every kg of nitrogen and phosphorus fertilizers applied.

Table 4.9. Agronomic efficiency of nitrogen and phosphorus fertilizer

Treatments	Agronomic efficiency			
	kg kg <sup>-1</sup> N		kg kg <sup>-1</sup> P	
	2020	2021	2020	2021
Sole maize	67.5 <sup>a</sup>	55.7 <sup>a</sup>	168.6 <sup>a</sup>	139.2 <sup>a</sup>
Maize no-topping	52.8 <sup>a</sup>	24.8 <sup>b</sup>	132.0 <sup>a</sup>	62.0 <sup>b</sup>
Maize topped	64.2 <sup>a</sup>	33.4 <sup>ab</sup>	160.6 <sup>a</sup>	83.5 <sup>ab</sup>
Doubled-up legume	-	-	-	-
Maize 2 plants per hill	53.9 <sup>a</sup>	38.7 <sup>ab</sup>	134.7 <sup>a</sup>	96.8 <sup>ab</sup>
Mbili-Mbili	62.4 <sup>a</sup>	38.2 <sup>ab</sup>	156.1 <sup>a</sup>	95.6 <sup>ab</sup>
Meru 513	66.2 <sup>a</sup>	36.3 <sup>ab</sup>	165.5 <sup>a</sup>	90.7 <sup>ab</sup>
Farmer practice	-	-	-	-
LSD	24.1	16.37	60.24	40.92
P-values	0.746	0.014	0.746	0.014

*Values of means in a column followed by different letters are significantly different*

Application of a kilogram of N and P fertilizer had a significant increase on maize yield indicating that fertilizer application is a beneficial investment in the study area. The highest gains in maize yield following a unit application of N and P fertilizer were observed in the 2020 season despite significant differences across treatment only being realized in 2021 season. This indicates that efficiency in N and P fertilizer is dependent on the seasonal weather. In addition, a strong association between seasonal weather and site was observed which indicates that benefits accrued from application of fertilizer are weather and location specific. Similar results on fertilizer response differing with changing seasonal weather were reported by Girma *et al.* (2007) while

Bonilla-Cedrez *et al.* (2021) and Acosta *et al.* (2011) observed its variability across sites. In addition, Amado *et al.* (2023) indicates existence of a strong influence of changes in seasonal weather on nutrient use efficiency. In their study, application of 180 kg N ha<sup>-1</sup> had the highest N efficiency in a season with good rainfall distribution while 60 kg N ha<sup>-1</sup> was the best in the consecutive season with low rainfall. While Kihara *et al.* (2021) proposed a bracket application of 50 kg N ha<sup>-1</sup> and 20 kg N ha<sup>-1</sup> as the optimal rate for smallholder fields in Babati, Mugi-Ngenga *et al.* (2022a) documents combining 90 kg N ha<sup>-1</sup> and 40 kg P ha<sup>-1</sup> as the best bet fertilizer rate, indicating variability in fertilizer recommendation. This study agrees with Bekunda *et al.* (2002) on the need of re-examining and revising fertilizer recommendations while accounting for the dynamic nature of soil fertility and seasonal weather variability to avoid sub-optimal application or wastage of this expensive resource.

Sole maize system had higher agronomic efficiency than maize-pigeon pea treatment (without topping) an indication of management practices such as crop diversification also influencing efficiency of fertilizer uptake. There is a possibility of occurrence of interspecific competition for applied nutrients by the intercropped pigeon pea that wasn't observed in sole maize system. However, innovative spatial arrangement such as Mbili-Mbili and manipulation of plant phenological properties through stripping, de-topping and use of drought-resistant maize hybrid seemed to offer remedy against the yield penalty. This study concurs with that of Ghosh *et al.* (2007) who recorded fertilizer response of up to 60 kg N ha<sup>-1</sup> in intercropped maize-legume systems while that of sole maize was as high as 120 kg N ha<sup>-1</sup>. In addition, conducting best management practices including proper spacing is a promising strategy for increasing agronomic efficiency of applied fertilizers (Roberts, 2007).

### *Hypothesis testing*

**H<sub>0</sub>:** Cropping systems do not influence biological nitrogen fixation of intercropped legumes.

Results of this study do not support a significant impact of cropping systems on biological nitrogen fixation (BNF) in intercropped legumes. The data does not support rejection of null hypothesis and conclude that under the conditions of this study, cropping systems do not influence BNF performance of legumes.

## 4.5 How Variations in Cropping Systems Influence Crop Physiological Characteristics and Physical-Chemical Properties of Soil in Three Eco-Zones of Babati

### 4.5.1 Pigeon pea Branch Production

The rate of pigeon pea branch production was significantly affected by the different treatments across the cropping seasons. Doubled-up legume had consistently more pigeon pea branches (by 1 to 6 branches per plants) production than the other treatments with pigeon pea (Table 4.10). Across the two seasons, Mbili-Mbili system had higher rate of pigeon pea branch production than improved maize-pigeon pea treatment with no de-topping. When rate of branching was assessed two weeks before maize harvesting in 2020, farmer practices had more pigeon pea branches per plant than improved maize-pigeon pea treatment with no de-topping. A statistically significant increase in pigeon pea branch development resulting from maize de-topping was recorded in the 2020 and not the 2021 season.

Table 4.10. Intercropping system effects on pigeon pea branch production during the 2020 and 2021 cropping season in Babati

Treatments	2020			2021	
	Pre- maize harvest	Post- maize harvest	Month prior-maize harvest	2 weeks prior-maize harvest	2 weeks post-maize harvest
Sole maize	-	-	-	-	-
Maize no de-topping	4.5 <sup>c</sup>	9.6 <sup>c</sup>	2.1 <sup>c</sup>	5.3 <sup>c</sup>	6.6 <sup>d</sup>
Maize de-topped	6.4 <sup>b</sup>	11.5 <sup>b</sup>	2.7 <sup>c</sup>	6.2 <sup>bc</sup>	6.8 <sup>cd</sup>
Doubled-up legume	8.7 <sup>a</sup>	15.9 <sup>a</sup>	4.9 <sup>a</sup>	8.7 <sup>a</sup>	10.9 <sup>a</sup>
Maize 2 plants per hill	6.0 <sup>b</sup>	11.7 <sup>b</sup>	2.4 <sup>c</sup>	5.9 <sup>bc</sup>	7.6 <sup>bc</sup>
Mbili-Mbili	6.4 <sup>b</sup>	11.6 <sup>b</sup>	3.6 <sup>b</sup>	6.9 <sup>b</sup>	8.4 <sup>b</sup>
Meru 513	5.6 <sup>bc</sup>	11.1 <sup>bc</sup>	2.6 <sup>c</sup>	5.7 <sup>c</sup>	7.1 <sup>c</sup>
Farmer Practice <sup>€</sup>	6.2 <sup>b</sup>	10.3 <sup>bc</sup>	-	-	-
<i>LSD</i>	1.38	1.83	0.74	1.02	0.88
<i>P-Value</i>	0.001	0.001	0.001	0.001	0.001

Values in same column followed by different letters are significantly different.

The level at which crops intercepts solar radiation has a positive influence on their rate of canopy development. Doubled-up legume had pigeon pea crop exposed to direct sunlight for the whole crop-growth cycle which might have activated earlier branch development relative to maize-based systems. Mbili-Mbili having earlier branch development than maize-pigeon pea system with no de-topping is an indicator of an existing potential for researchers to develop more cropping systems that can reduce the challenge of legume-shading by maize. The increase in radiation interception by intercropped legumes can be achieved through re-configuration of plant spatial patterns (Walelign, and Demisie, 2012) as is the case with Mbili-Mbili or modification of phenological parts like conducting maize de-topping (Ahmed *et al.*, 2007). While exploration of the influence of plant spatial configurations and other management practices like de-topping on phenological development of intercropped legumes is an emerging research area (Madembo *et al.*, 2020), Studies like Thuita *et al.* (2011) and Mucheru-Muna *et al.* (2010) associated the spatial improvement of MBILI technology with improved legume yields. In addition, Woomer *et al.* (2004) indicated shading of legumes through interception of solar radiation by maize under conventional maize-legume system causes sub-optimal radiation use efficiency on understorey legumes. This compromises their biological nitrogen fixation capacity and ability to develop nutrient-rich biomass for improving soil fertility. Like indicated by Kimaro *et al.* (2009) and Madembo *et al.* (2020) more research along this research frontier is needed to assess the magnitude of impacts different levels of exposure to solar radiation interception have on phenological development of different species of intercropped legumes.

#### ***4.5.2 Effects on Pigeon pea Flowering***

Pigeon pea flowering was significantly affected by both the treatments and season when assessment was conducted. Doubled-up legume had significantly higher number of flowered plants for each sampling period and season relative to other systems (Table 4.11). In the 2021 cropping season, treatment with de-topped maize had significantly higher number of flowered pigeon pea plants, both two weeks prior and at the period following maize harvest, relative to treatment with maize-pigeon pea intercrop without de-topping. In the same season, Mbili-Mbili had increased number of flowered pigeon pea plants relative to maize-pigeon pea system without de-topping.

Table 4.11 Treatment effects on the rate of pigeon pea flowering during the 2020 and 2021 seasons in Babati

Treatments	Month pre- Mz harvest	2 weeks pre- Mz harvest	2 weeks post- Mz harvest	Month post- Mz harvest	Month pre- Mz harvest	2 weeks pre- Mz harvest	Month post- Mz harvest
	No. of flowered plants in 2020				No. of flowered plants in 2021		
Sole maize	-	-	-	-	-	-	-
Maize no de-topping	0.9 <sup>b</sup>	4.1 <sup>b</sup>	12.9 <sup>b</sup>	28.3 <sup>b</sup>	3.6 <sup>c</sup>	14.5 <sup>d</sup>	20.27 <sup>cd</sup>
Maize de-topped	1.3 <sup>b</sup>	4.7 <sup>b</sup>	11.2 <sup>b</sup>	34.6 <sup>b</sup>	6.1 <sup>b</sup> <sup>c</sup>	16.6 <sup>c</sup>	22.2 <sup>b</sup>
DUL	8.7 <sup>a</sup>	22.8 <sup>a</sup>	63.9 <sup>a</sup>	91.5 <sup>a</sup>	22.2 <sup>a</sup>	32.7 <sup>a</sup>	38.3 <sup>a</sup>
Maize 2 plants per hill	2.5 <sup>b</sup>	7.4 <sup>b</sup>	15.9 <sup>b</sup>	31.7 <sup>b</sup>	5.7 <sup>b</sup> <sup>c</sup>	13.6 <sup>d</sup>	19.8 <sup>d</sup>
Mbili-Mbili	2.3 <sup>b</sup>	5.9 <sup>b</sup>	16.9 <sup>b</sup>	30.1 <sup>b</sup>	8.0 <sup>b</sup>	19.9 <sup>b</sup>	21.7 <sup>b</sup> <sup>c</sup>
Meru 513	1.9 <sup>b</sup>	6.7 <sup>b</sup>	15.6 <sup>b</sup>	25.67 <sup>b</sup>	5.0 <sup>b</sup> <sup>c</sup>	16.8 <sup>c</sup>	22.67 <sup>b</sup>
<i>LSD</i>	<i>1.81</i>	<i>5.46</i>	<i>9.10</i>	<i>13.61</i>	<i>4.02</i>	<i>0.68</i>	<i>1.60</i>
<i>P-Value</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>	<i>0.001</i>

*Mz refers to maize planted with the treatment. Values in same column followed by different letters are significantly different.*

The rate of pigeon pea flowering followed a similar pattern as branch development where doubled-up legume had an earlier and higher proportion of flowers following exposure to more solar radiation than other treatments. In addition, the 130 cm spacing created between the double maize rows accompanied by leaf stripping improved the rate of flowering in Mbili-Mbili compared to maize-pigeon pea system. This shows existence of relationship between pigeon pea exposure to solar radiation and potential yield of the crop (Walter and Kromdijk, 2022). The effect of shading was also recorded when treatments with and without de-topping of maize were compared, which endorses the earlier finding of de-topping 2 t ha<sup>-1</sup> of maize resulting in 93.4% increase in pigeon pea biomass. This also agrees with Lugassi-Ben-Hamo *et al.* (2010) on 26% reduction in flower formation due to crop exposure to shading. Indeed, crop productivity is strongly linked to its efficiency of utilization of photosynthetically active radiation (Morais *et al.*, 2006). This is because light improves availability of carbohydrates that are produced through photosynthesis, a process that is light-dependent (Monerri *et al.*, 2011). Therefore, developing intercropping innovations that allow pigeon pea to optimize solar radiation interception can help to ensure that the produced flowers are retained.

#### ***4.5.3 Maize Leaf Chlorophyll***

The density of leaf chlorophyll in maize was significantly affected by treatments and growth stages when sampling was conducted. In the 2019 cropping season, treatments with sole maize, maize-pigeon pea intercrop without de-topping and Meru 513 variety had between 5 to 7% higher leaf chlorophyll content than Mbili-Mbili system (Table 4.12). Despite having lower chlorophyll content during the period of active plant elongation (V8-V12), Mbili-Mbili had similar level of chlorophyll accumulation as other treatments during the maize reproductive stages. A similar decline in maize leaf chlorophyll under Mbili-Mbili was also observed at the early vegetative stages in the 2020 season.

Table 4.12 Effect of cropping systems on maize leaf chlorophyll

Treatment	2019			2020			2021		
	V6- V7	V8- V12	VT- R3	V6- V7	V8- V12	VT- R3	V6- V7	V8- V12	
Sole maize	42.8 <sup>a</sup>	49.4 <sup>a</sup>	37.3 <sup>a</sup>	42.8 <sup>ab</sup>	49.6 <sup>a</sup>	39.4 <sup>a</sup>	50.4 <sup>a</sup>	48.9 <sup>a</sup>	
Maize no de-topping	43.8 <sup>a</sup>	48.4 <sup>ab</sup>	35.7 <sup>a</sup>	40.5 <sup>b</sup>	47.8 <sup>a</sup>	39.7 <sup>a</sup>	50.3 <sup>a</sup>	48.6 <sup>a</sup>	
Maize de-topped	42.8 <sup>a</sup>	47.8 <sup>abc</sup>	36.6 <sup>a</sup>	44.0 <sup>a</sup>	48.8 <sup>a</sup>	40.5 <sup>a</sup>	49.7 <sup>a</sup>	48.3 <sup>a</sup>	
Doubled-up legume	-	-	-	-	-	-	-	-	
Maize 2 plants per hill	41.7 <sup>a</sup>	46.6 <sup>bc</sup>	36.1 <sup>a</sup>	42.5 <sup>ab</sup>	48.9 <sup>a</sup>	40.7 <sup>a</sup>	50.4 <sup>a</sup>	49.1 <sup>a</sup>	
Mbili-Mbili	41.9 <sup>a</sup>	46.3 <sup>c</sup>	35.1 <sup>a</sup>	40.4 <sup>b</sup>	50.0 <sup>a</sup>	41.1 <sup>a</sup>	49.8 <sup>a</sup>	48.3 <sup>a</sup>	
Meru 513	44.0 <sup>a</sup>	49.5 <sup>a</sup>	37.8 <sup>a</sup>	44.1 <sup>a</sup>	49.4 <sup>a</sup>	39.0 <sup>a</sup>	50.4 <sup>a</sup>	48.1 <sup>a</sup>	
<i>LSD</i>	2.9	2.1	2.91	2.5	2.18	2.8	2.68	2.2	
<i>P value</i>	0.5	0.01	0.43	0.01	0.45	0.69	0.99	0.93	

*Values in same column followed by different letters are significantly different*

Similar levels of maize leaf chlorophyll across the study period, except for Mbili-Mbili in the early growth stages of 2019 and 2020 seasons, is an indicator that plant spatial configurations in different treatments did not pose significant negative effects on maize production. The growth stages between V6 and V10 represents a period of active maize elongation which is characterized by an increased demand for growth resources for maize and beans under Mbili-Mbili. However, this period usually coincides with a prolonged dry spell (extending between the month of February and March) which negatively affects development of food crops in Babati. Indeed, some farmers prefer to plant beans in the month of March to escape the dry spell, though this exposes young beans to shading by maize, affecting yields. Other farmers plant drought tolerant maize varieties like Meru 513 or sole maize because the two treatments have reduced competition for moisture (hence dense chlorophyll) than the rest of the treatments amidst unfavorable weather. The estimation of chlorophyll in crops as a proxy of the amount of nitrogen accumulated at specific stages of maize growth was, and has been, used as a strategy for assessing N limitations in growing crop (Rostami *et al.*, 2008). The variation in leaf chlorophyll level between the different maize varieties despite uniformity in the field management operations applied agrees with Sheridan *et al.* (2012) and Kaur *et al.* (2012) that differences in maize leaf chlorophyll is a factor of variation in the maize varieties planted, stage of crop growth or management practices employed.

The weather condition in the 2019 season had adverse effects on systems with more crop population such as Mbili-Mbili, as evident by lower chlorophyll levels than other treatments. The negative effect on leaf chlorophyll level was because of the poor rainfall distribution and amount which result in some level of competition for moisture and affects uptake of nutrients by the crops. A contrast was observed in the 2020 season when rainfall of up to 2000 mm was received in the vegetative and reproductive stages of maize. Despite the benefits of increased production of intercropped legumes, cropping systems with high plant population/density like Mbili-Mbili might be vulnerable to in-season droughts or prolonged dry spells as observed in this and other studies (Li *et al.*, 2021). Weather associated challenges (i.e., either rainfall extremes) might not only result in reduced leaf chlorophyll (Rorie *et al.*, 2011) in maize, but loss of intercropped bean which are more vulnerable to changes in weather (Cirino *et al.*, 2015) as was evident during the 2019 season.

It was interesting to see Mbili-Mbili having lower chlorophyll level during the early stages of plant development, and later being able to recover and attain similar chlorophyll levels and grain yield as other treatments. This is a good indicator of the stability (Samborski *et al.*, 2009) of Mbili-Mbili, despite supporting multiple rows and species of crops, than other maize-legume systems. Results from the 2019 season shows the importance of adopting robust intercropping systems involving crop diversification because despite having some level vulnerability to extreme weather (Cirino *et al.*, 2015; Li *et al.*, 2021), it is still resilient to weather associated shocks (Renwick *et al.*, 2020). In addition, such an innovation might have greater economic benefit than the common 1:1 intercropping system (Degani *et al.*, 2019).

#### **4.5.4 Light Interception and Leaf Area Index**

Except for 2019, where vegetative cover might have been influenced by the poor weather conditions, a similar trend of treatment effect on photosynthetically active radiation and leaf area index was observed during the 2020 season (Table 4.13). The amount of solar radiation recorded in the field during photosynthetically active radiation assessment significantly varied across sites in the order of Sabilo > Riroda > Gallapo with 1595, 1418 and 1329 Wm<sup>2</sup> ( $P \leq 0.001$ ). This resulted in a significant variability in solar radiation interception by crops in the different sites with higher fractions being recorded in Sabilo (0.648) compared to Gallapo (0.538) and Riroda (0.536). A significant interaction on light fractions were observed between the different treatments and sites ( $P \leq 0.01$ ). Fraction of radiation interception was significantly higher in conventional maize-pigeon

pea (no-detopping) than in sole maize system in greater part of the season. Fractions of solar radiation intercepted by Mbili-Mbili was significantly higher from early vegetative stages (V6-V8 maize stages) of the crop until maize harvesting i.e., 50% flowering of intercropped pigeon pea crop. Doubled-up legume system had consistently lower ( $P \leq 0.05$ ) fraction of intercepted radiation compared to maize-based systems. Upon harvesting of maize, the fraction of solar radiation intercepted by pigeon pea crop under doubled-up legume was significantly higher than pigeon pea intercropped with maize. De-topping of maize at late reproductive stages (physiological maturity) resulted to a significant reduction in the fraction of radiation intercepted relative to system with no de-topping. The reduced fraction of intercepted radiation of upto 7% relative to treatment with no de-topping can be associated with more light penetrating to the intercropped pigeon pea following reduction of shading effect by maize. Leaf area index was higher in maize-pigeon pea intercropping than in the monocrop systems for the period between early vegetative stages of maize to its physiological maturity. Mbili-Mbili had consistently higher leaf area index between early vegetative stages to early reproductive stages which was not the case with other treatments.

Table 4.13. Intercropping effect on light interception and leaf area index during the LR 2019 and 2020 seasons in Babati Tanzania

Treatment	Early vegetative	Late vegetative	Early reproductive	Late reproductive	Flower initiation	Half flowered	Podding
Fraction of light intercepted and LAI in 2019 season							
Sole maize	0.224 (0.43)						
Maize no de-topping	0.190 (0.45)				0.304 <sup>cd</sup> (2.47 <sup>a</sup> )		0.253 <sup>ab</sup> (0.74)
Maize de-topped	0.208 (0.38)				0.249 <sup>d</sup> (1.22 <sup>b</sup> )		0.246 <sup>b</sup> (0.82)
Doubled-up legume	0.179 (0.39)				0.525 <sup>a</sup> (2.76 <sup>a</sup> )		0.278 <sup>a</sup> (0.77)
Maize 2 plants per hill	0.207 (0.43)				0.335 <sup>bc</sup> (2.28 <sup>a</sup> )		0.248 <sup>ab</sup> (0.66)
Mbili-Mbili	0.213 (0.47)				0.378 <sup>b</sup> (2.49 <sup>a</sup> )		0.23 <sup>bc</sup> (0.61)
Meru 513	0.141 (0.29)				0.350 <sup>bc</sup> (3.05 <sup>a</sup> )		0.2084 <sup>c</sup> (0.69)
<i>LSD</i>	0.060				0.070 (1.03)		0.030 (0.28)
<i>P-value</i>	0.078				0.001 (0.02)		0.001 (0.72)
Fraction of light intercepted and LAI in 2020 Season							
Sole maize	0.288 <sup>b</sup> (0.92 <sup>ab</sup> )	0.714 <sup>b</sup> (3.04 <sup>bc</sup> )	0.846 <sup>bc</sup> (4.14 <sup>ab</sup> )	0.711 <sup>ab</sup>	0.685 <sup>d</sup>	0.722 <sup>bcd</sup>	
Maize no de-topping	0.336 <sup>a</sup> (0.95 <sup>ab</sup> )	0.710 <sup>b</sup> (2.93 <sup>bc</sup> )	0.886 <sup>a</sup> (4.34 <sup>a</sup> )	0.701 <sup>ab</sup>	0.724 <sup>bc</sup>	0.744 <sup>ab</sup>	0.299 <sup>b</sup>
Maize de-topped	0.284 <sup>b</sup> (0.84 <sup>b</sup> )	0.768 <sup>a</sup> (3.12 <sup>ab</sup> )	0.864 <sup>b</sup> (4.24 <sup>a</sup> )	0.649 <sup>c</sup>	0.698 <sup>cd</sup>	0.676 <sup>e</sup>	0.226 <sup>cd</sup>
Doubled-up legume	0.131 <sup>d</sup> (0.42 <sup>d</sup> )	0.290 <sup>d</sup> (0.82 <sup>e</sup> )	0.395 <sup>e</sup> (1.09 <sup>c</sup> )	0.386 <sup>d</sup>	0.533 <sup>f</sup>	0.737 <sup>bc</sup>	0.485 <sup>a</sup>
Maize 2 plants per hill	0.244 <sup>c</sup> (0.63 <sup>c</sup> )	0.713 <sup>b</sup> (2.74 <sup>c</sup> )	0.819 <sup>d</sup> (3.85 <sup>b</sup> )	0.675 <sup>bc</sup>	0.619 <sup>e</sup>	0.694 <sup>de</sup>	0.270 <sup>bc</sup>
Mbili-Mbili	0.347 <sup>a</sup> (1.09 <sup>a</sup> )	0.783 <sup>a</sup> (3.40 <sup>a</sup> )	0.836 <sup>cd</sup> (4.12 <sup>ab</sup> )	0.730 <sup>a</sup>	0.774 <sup>a</sup>	0.784 <sup>a</sup>	0.208 <sup>d</sup>
Meru 513	0.296 <sup>b</sup> (0.84 <sup>b</sup> )	0.667 <sup>c</sup> (2.37 <sup>d</sup> )	0.834 <sup>cd</sup> (4.40 <sup>a</sup> )	0.681 <sup>bc</sup>	0.746 <sup>ab</sup>	0.695 <sup>cde</sup>	0.289 <sup>b</sup>
<i>LSD</i>	0.032 (0.13)	0.032 (0.22)	0.021 (0.24)	0.041	0.038	0.043	0.045
<i>P-value</i>	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001	0.001	0.001	0.001

Data in parenthesis represent value of leaf area index in the different seasons and maize growth stages. Early vegetative =maize between V6-V8, Late vegetative=maize around VII, Early reproductive= maize around R1, Late productive= maize around R4 stages of growth, Flower initiation= pigeon pea at early flowering, Half flowered= pigeon pea at 50% flowering and Podding= 50% podding. Data on fraction of radiation inception between late vegetative and late reproductive stages of maize in 2019 is missing due to technical hitch that occurred to the AccuPAR LP-80 device.

The agro-ecological positioning of the three sites resulted in some sites receiving more solar radiation than others. This might have led to average maize and pigeon pea yields obtained in Sabilo (i.e., 4.4 and 0.9 t ha<sup>-1</sup>) being significantly higher than that of Gallapo (i.e., 3.3 and 0.7 t ha<sup>-1</sup>) and Riroda (i.e., 3.2 and 0.3 t ha<sup>-1</sup>) villages. Intercropping systems are also effective utilizers of PAR relative to monocrop systems. For example, Mbili-Mbili is a more robust intercropping system having three strips of two legume species adjacent the double maize row relative to other treatments with a single strip or no legume. The spatial configuration of Mbili-Mbili where large spacing is created to accommodate multiple strips of legumes allows more light penetration and interception by understorey legumes. However, Mbili-Mbili had reduced radiation interception at 50% podding a condition associated with the space that was created when maize was harvested. This could have partly resulted in sub-optimal photosynthetically active radiation use efficiency (Muurinen and Peltonen-Sainio, 2006) but also helped pigeon pea in the treatment to have significantly higher branch and flower development (Angadi *et al.*, 2022) than in the shaded maize-pigeon pea treatments. The multiple crop species within Mbili-Mbili provides some level of canopy development at variable times of the season, starting with beans, maize, and later pigeon pea, which enhances solar radiation interception and use efficiency in the greater part of the season, promoting soil health (Kumar *et al.*, 2022). This makes the system to be a suitable option for weed suppression and conservation of soil moisture (Chimonyo *et al.*, 2016) while reducing the erosive capacity of raindrops (Danquah *et al.*, 2022).

During the period before pigeon pea podding, the level of canopy cover provided by doubled-up legume was low due to slow growth of pigeon pea and reduced canopy cover created by bush bean, exposing the soil to direct radiation. This makes doubled-up legume comprising integration of bean and pigeon pea to be inefficient radiation user thus negatively impacting on soil health (Kocira *et al.*, 2020). The low canopy cover by doubled-up legume is nonetheless helpful in promoting the productivity of pigeon pea (Kumar, 2019), as was evident by the dense plant canopy at podding stage and the high solar radiation overall. In addition, maintaining minimum level of shading was identified to be also efficient in enhancing radiation use and promoting grain yield. For example, de-topping 2 t ha<sup>-1</sup> of maize biomass showed potential of enhancing yield of intercropped pigeon pea by 15.4% for grain and 94.3% for haulms, but with diminishing returns if biomass removal was exceeded. This agrees with finding by Kumar *et al.* (2023) who observed a

2.22 gMJ<sup>-1</sup> of radiation use efficiency at 75% of pigeonpea shading relative to 1.6 gMJ<sup>-1</sup> when the crop was cultivated under no shade.

In seasons characterized by low and/or poorly distributed rainfall, treatments with reduced leaf area index, such as the early growth stages of doubled-up legume, are prone to high evaporation and moisture stress with a potential of causing economic losses of upto 26%. Sole maize treatment also poses detrimental effects on soil especially after maize harvest, a period when soil is left bare and exposed to agents of erosion. Integrating legumes such as pigeon pea in either bean or maize monoculture systems would help to promote a year-round soil cover (Kimaro *et al.*, 2009). Besides, the high leaf area index under Mbili-Mbili, attributed to the multiple species of crops, can be used as a strategy for moderating extreme weather parameters such as soil temperatures (Borowy, 2012), promoting soil and water conservation and crop water productivity (Sharaiha and Hadidi, 2007) which forms an important yield enhancer (Nyawade *et al.*, 2019).

#### ***4.5.5 Soil Moisture and Temperature***

Soil moisture and temperature levels were significantly affected by site and not by treatments. Averaged across the cropping seasons, Sabilo and Gallapo villages had significantly higher soil moisture content, in at least two of the three seasons, than Riroda ( $P \leq 0.05$ ; Figure 4.5). Soil moisture ranged between 0.089 – 0.239 m<sup>3</sup>m<sup>3</sup> at V6 and R4 maize stages, respectively, in the 2019, 0.036-0.162 m<sup>3</sup>m<sup>3</sup> at pigeon pea maturity and V6 stage of maize, respectively, in the 2020 and 0.047-0.195 m<sup>3</sup>m<sup>3</sup> at pigeon pea maturity and R4 maize stage, respectively, in the 2021 seasons. Soil temperatures were highest at the period between V6-V9 and lowest between silking and physiological maturity of maize with values ranging between 24.2 - 39.4 °C, 29.4 -31.9 °C and 25.6 - 32.7 °C in the 2019, 2020 and 2021 seasons, respectively.

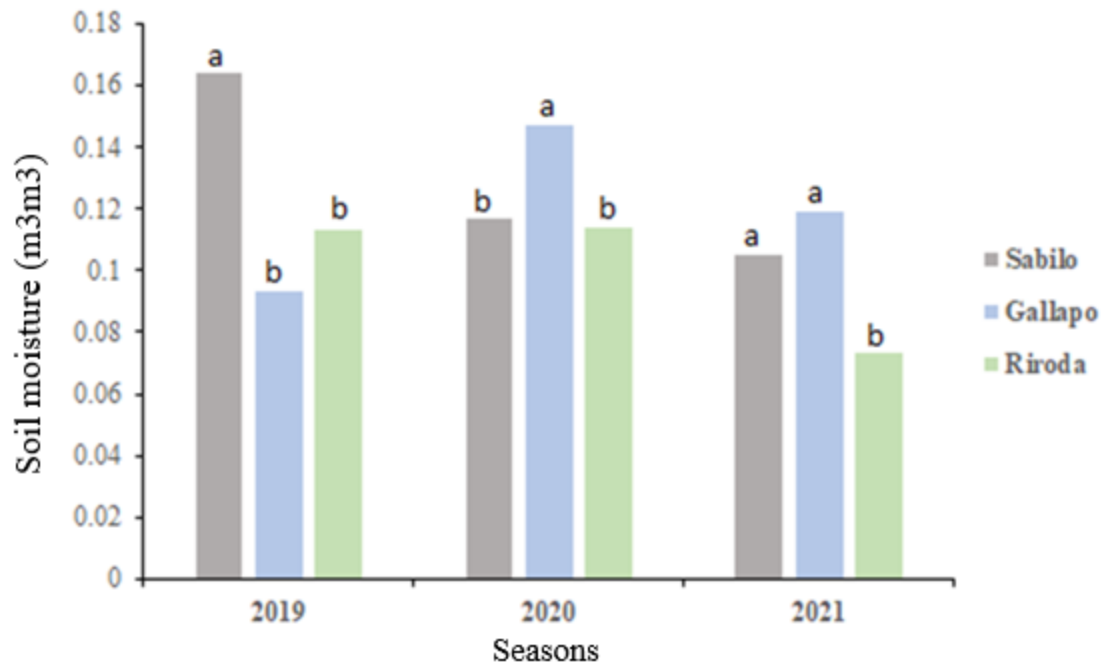


Figure 4.5. Soil moisture variation as affected by sites and seasons.

The soil textural characteristics had a great bearing on the amount and duration moisture was retained by the soil. In Riroda, the soils were generally sandy, with levels upto 80.3% (Mugi Ngenga *et al.*, 2022), which contributed to their lower soil moisture holding capacity relative to those in Sabilo and Gallapo. In seasons characterized by poor rainfall amounts, such as the 2019 and 2021 seasons which recorded <404 mm, sandy soil easily losses moisture as was the case with Riroda site. Low soil moisture content strongly relates with increased temperatures (Seneviratne *et al.*, 2010; Meng and Shen 2014) which is detrimental for crop production and the general soil health. This is because uptake of soil nutrients (Querejeta *et al.*, 2021) and the dynamics controlling both preservation and breakdown of organic matter (Green *et al.*, 2019) are directly and strongly influenced by soil moisture and temperature levels. The challenge of high moisture loss could have been accelerated by low soil organic matter content (Mulumba and Lal, 2008) evident by soil carbon content of <1% as reported during this study. The low moisture condition and a corresponding high temperature between V6 and V9 of maize growth was also coincidentally recorded during an in-season drought period that occurs between the month of February and March as also reported by Lamborn (2010). Sandy soils have good drainage but poor moisture holding capacity that may result in more pronounced in-season dry spells in Riroda and regions with similar soil characteristics (Ceballos *et al.*, 2002). Use of ISFM practices like manure and organic matter

retention are recommended for improving soil structural stability (Nyamangara and Nyagumbo, 2011) and moisture conservation potential (Zhou *et al.*, 2020) of sandy soils.

*Hypothesis testing*

**H<sub>0</sub>:** Crop physiological characteristics and physical-chemical properties of soil are not influenced by different cropping systems and agro-ecological conditions.

The results of this study indicate that crop physiological characteristics, such as pigeon pea branch and flower development, legume grain yields, and photosynthetically active radiation (PAR), are significantly influenced by cropping systems. This allows for the rejection of the null hypothesis in relation to crop physiological characteristics. However, soil physical-chemical properties were found to be influenced by agro-ecological conditions, rather than the cropping systems. As such, the results fail to reject the null hypothesis with respect to the effect of cropping systems on soil physical-chemical properties.

**4.6 Influence of Farmer Gender on Household Decisions Making Process on Implementation of Improved Intercropping Innovations**

**4.6.1 Ranking of Sustainable Intensification Indicators by Gender**

In the 2020 season, 105 farmers participated in technology ranking and rating exercise relative to 103 farmers in the 2021 season (Table 4.14). For all seasons, participation by male farmers in technology testing exercise was higher i.e., 24% in the 2020 and 32% in the 2021 seasons, than that of female farmers. In addition, farmer participation in Sabilo village was higher than that of Gallapo.

Table 4.14. Farmer participation in technology assessment exercise during the 2020 and 2021 seasons in Babati

Farmer gender	2020		2021	
	Gallapo	Sabilo	Gallapo	Sabilo
Male	25	40	31	37
Women	20	20	12	23

A similar trend on gender-based preferences to technologies under test was observed in both the 2020 and 2021 seasons. Female farmers preferred technologies that were high yielding and those that had a potential of ensuring food security of their households (Table 4.15). On the contrary, male farmers focused on technologies that were high yielding and that would meet both the food and income demands of their households. The productivity aspects used by farmers to guide their ranking decisions included number of cobs per plant, proportion of cob filling, cob and grain sizes, crop arrangement, crop species planted, amount of biomass, labor requirements and more specifically, if maize is part of the intercropping component.

Table 4.15. Ranking of sustainable intensification indicators by female and male farmers during the 2020 and 2021 seasons in Gallapo and Sabilo villages of Babati

Crop production indicators	2020				2021				Average
	Gallapo		Sabilo		Gallapo		Sabilo		
	Female	Male	Female	Male	Female	Male	Female	Male	
Yield	1	1	2	1	1	1	1	1	1
profitability	2	3	3	2	2	2	3	2	2
Labor requirement	4	4	4	4	4	4	4	4	4
Food security	3	2	1	3	2	3	2	3	2

The outcomes of technology ranking were different between the gender in the two sites and seasons. Female farmers in Gallapo highly ranked maize de-topped and maize 2 plants per hill while those in Sabilo had a high preference for Mbili-Mbili in the 2020 and 2021 seasons, respectively (Table 4.16). Contrary, male farmers in Gallapo ranked Mbili-Mbili and maize 2 plants per hill while those in Sabilo had sole maize and Mbili-Mbili as their best technologies in the 2020 and 2021 seasons, respectively. Key indicators farmers considered during ranking of technologies included the potential yields, income, food security and integration of both maize and pigeon pea. While Mbili-Mbili was ranked as the best technology across gender and seasons because of integration of three crop species, doubled-up legume had the lowest rank because it lacked maize as part of the intercropping component. Absence of pigeon pea in sole maize also contributed to the technology being accorded a lower rank. Interestingly, female farmers had more preference to technologies with higher biomass for use as livestock fodder than their male counterpart.

Table 4.16. Technology ranking by male and female farmers in Gallapo and Sabilo villages during the 2020 and 2021 seasons in Babati

Technologies	2020		2021		Reasons behind the ranking
	Gallapo	Sabilo	Gallapo	Sabilo	
Female Group					
Sole maize	6	6	4	4	High income and fodder from maize; low income due to lack of pigeon pea; food insecure; provides maize cores for fuel
Maize no de-topping	5	2	6	5	Moderate yield; low plant density; low labor requirements; provides fodder from stover and husks; pigeon pea improves moisture retention and fertility
Maize de-topped	1	3	2	2	Two cobs per plant; good pigeon pea productivity after de-topping; high yield and income; toppings, stover and husks provides animal fodder; pigeon pea improves moisture retention and fertility; provides enough biomass for fuel
Doubled-up legume	7	7	3	6	High legume yields but low income and food insecure because maize was missing; improves soil fertility; source of vegetables
Maize 2 plants per hill	2	5	1	3	Have 2 cobs per plant: high yields and income; food secure; reduced labor; source of fodder; provides fuel; improves soil fertility
Mbili-Mbili	3	1	5	1	Food secure; high income generation because of different crop species; diverse source of animal fodder; improves soil fertility
Meru 513	4	4	7	7	Low plant biomass; small size of grain; food secure; improves soil fertility
Male Group					
Sole maize	7	1	6	7	No pigeon pea hence low income and food security; poor crop performance
Maize no de-topping	5	2	3	5	Some plant lacked cobs; moderate cob sizes; food secure, good income
Maize de-topped	4	5	2	2	Have two cobs per plant; large cobs; de-topping improves pigeon pea yield
DUL	6	7	7	6	Lacks maize; does not guarantee food security
Maize 2 plants per hill	2	3	1	4	Have big cobs; plants have dense chlorophyll; high yields hence food secure; profitable; low labor requirement due to good spacing;
Mbili-Mbili	1	4	4	1	Some plants did not have cobs; prospects of high-income generation from 2 legumes; food secure and crop diversification; labor intensive
Meru 513	3	6	5	3	A good maize and pigeon pea yield, hence food secure, high biomass for livestock fodder

The socio norms, roles and status associated with gender of participant farmers were identified as guiding farmers' decision, preferences, and choice of technologies under assessment. Men are known to dominate and control decisions relating to land and incomes of smallholder households an attribute that can be linked to their focus on attainable yield and profitability of a technology. Women preferred technologies with potentially higher yield and ability to meet the food security needs of their households. Mbili-Mbili was highly ranked since it met the basic requirements set by farmers including potentially high yields (from maize and intercropped legumes), crop diversification resulting in food security of smallholder households and had more stable revenue from the two species of legumes. This concurs with Kinyua *et al.* (2023) who indicated a 95% willingness to scale up the technology, which they associated with potential for meeting their household food and nutrition requirements. Despite the willingness to adopt, farmers had initially showed some reservation on implementing Mbili-Mbili which they associated with likelihood of causing competition that might result in yield loss. Such reservations were reported by Muyanga and Jayne (2006) who indicated that farmers with limited resources shy from trying new technologies to avoid losing their investment.

The preference and relevance farmers placed on different crop species highly varied across gender depending on the benefits each group perceived they would derive from the component crops. For example, pigeon pea is a common legume in Babati with perceptions of its value differing across farmer gender. Male farmers value systems associated with high pigeon pea production because of the income (Me-Nsope *et al.*, 2015) they derive from sale of the crop. Contrary, female farmers place little focus on the revenue generated from pigeon pea citing lack of involvement by their male spouses in making decisions relating to sale and use of proceeds generated from the crop (Ayenan *et al.*, 2017; Matere *et al.*, 2022). However, women were still benefiting from other pigeon pea products such as green pods for vegetable, biomass for livestock and stems for fuelwood (Mpairwe and Mutetikka, 2022). In majority of farmer households in the study area, dairy cows were introduced through women groups (Krietzman, 2019) and mainly reared under zero grazing systems (Mpairwe and Mutetikka, 2022). Not only do women feed them but they do also control proceeds from milk sale (Fischer *et al.*, 2018) and would therefore select any technology with promisingly high biomass generation, an aspect that lacked in male participants.

Despite beans being considered a women crop, female farmers had a lower preference on doubled-up legume which they associated with lacking maize, an essential food crop for majority of smallholder households in the area. If adopted by women, it is likely that men would also impose their control over doubled-up legume. This is not because they are already in charge of the pigeon pea companion but because they would commercialize the beans despite women providing significant role in labor provision (De Brauw, 2015). Njuki *et al.* (2011) indicated women mainly have control over crops produced for subsistence purposes. Therefore, female farmers would have a greater control of bean cultivated under smaller unit of scale like in Mbili-Mbili which Kinyua *et al.* (2023) reported to have 1.5 t ha<sup>-1</sup> lesser bean production than doubled-up legume.

#### ***4.6.2 Technology Ranking and Rating as Affected by Gender***

Technology rating by male and female farmers varied across treatments and cropping seasons (Table 4.17). Averaged across the sites, female farmers rated their best technologies as sole maize and Maize 2 plants per hill in the 2020 and 2021 seasons, respectively. Contrary, male farmers rated sole maize and Maize de-topped  $\geq$  Mbili-Mbili as their best technologies in the 2020 and 2021 seasons, respectively. Often, Mbili-Mbili was rated the second best while Maize (Meru 513) had a low rating across gender and cropping seasons.

Table 4.17. Rating of technologies by male and female farmers as guided by sustainable intensification indicators

Technology	prod	Prof	sec	Lab	Tot	Ave	Rank	prod	Prof	Sec	Lab	Tot	Ave	Rank
	2020							2021						
Female farmers														
Sole maize	1.0	3.0	1.5	2.0	<b>7.5</b>	<b>1.9</b>	<b>1</b>	2.0	2.5	2.5	3.0	<b>10.0</b>	<b>2.5</b>	<b>4</b>
Maize no de-topping	2.5	3.0	2.5	2.0	<b>10.0</b>	<b>2.5</b>	<b>5</b>	2.5	2.5	3.5	2.5	<b>11.0</b>	<b>2.8</b>	<b>4</b>
Maize de-topped	2.5	3.0	2.5	2.0	<b>10.0</b>	<b>2.5</b>	<b>5</b>	2.0	2.0	2.5	2.0	<b>8.5</b>	<b>2.1</b>	<b>3</b>
Doubled-up legume	1.5	1.5	3.0	3.0	<b>9.0</b>	<b>2.3</b>	<b>3</b>	2.5	2.5	2.0	2.5	<b>9.5</b>	<b>2.4</b>	<b>6</b>
Maize 2 plants per hill	1.5	2.0	3.0	2.5	<b>9.0</b>	<b>2.3</b>	<b>3</b>	1.5	1.5	1.5	2.5	<b>7.0</b>	<b>1.8</b>	<b>1</b>
Mbili-Mbili	1.5	2.5	3.0	1.0	<b>8.0</b>	<b>2.0</b>	<b>2</b>	1.5	1.0	2.0	3.5	<b>8.0</b>	<b>2.0</b>	<b>2</b>
Meru 513	3.0	3.0	2.5	2.5	<b>11.0</b>	<b>2.8</b>	<b>7</b>	3.0	3.0	3.0	3.0	<b>12.0</b>	<b>3.0</b>	<b>7</b>
Male farmers														
Sole maize	2	2.5	1.5	2.5	<b>8.5</b>	<b>2.1</b>	<b>1</b>	2.5	3.0	3.0	1.5	<b>10.0</b>	<b>2.5</b>	<b>4</b>
Maize no de-topping	2	3	1.5	3	<b>9.5</b>	<b>2.4</b>	<b>2</b>	3.0	3.0	3.0	3.0	<b>12.0</b>	<b>3.0</b>	<b>6</b>
Maize de-topped	2.5	3	2	3	<b>10.5</b>	<b>2.6</b>	<b>5</b>	1.5	1.5	1.5	3.0	<b>7.5</b>	<b>1.9</b>	<b>1</b>
Doubled-up legume	2.5	3.5	3.5	3.5	<b>13</b>	<b>3.3</b>	<b>7</b>	2.5	2.5	2.5	2.5	<b>10.0</b>	<b>2.5</b>	<b>4</b>
Maize 2 plants per hill	2.5	3	2.5	2.5	<b>10.5</b>	<b>2.6</b>	<b>5</b>	2.0	1.5	1.5	3.0	<b>8.0</b>	<b>2.0</b>	<b>3</b>
Mbili-Mbili	2.5	2	3.5	1.5	<b>9.5</b>	<b>2.4</b>	<b>2</b>	2.0	2.0	2.0	1.5	<b>7.5</b>	<b>1.9</b>	<b>1</b>
Meru 513	2	3	2.5	2.5	<b>10</b>	<b>2.5</b>	<b>4</b>	3.0	3.0	3.0	3.0	<b>12.0</b>	<b>3.0</b>	<b>6</b>

Labor requirements of the technologies under test played a key role in influencing their preference by participant farmers. Female farmers in Gallapo had a low ranking for Mbili-Mbili system during the two seasons of assessment which they attributed to its high labor requirement during planting. A similar trend was observed in Sabilo in the 2020 season where despite sole maize system being ranked the lowest because of lacking legumes, male farmers still preferred it due to ease in planting and weeding. Male farmers contribute a significant role in providing labor for land preparation (Kizito *et al.*, 2022), including uprooting pigeon pea stumps to ease workability by animal and/or tractor drawn plough, a burden they would forgo by adopting sole maize systems. Despite studies (Lee *et al.*, 2006; Kassie *et al.*, 2013) describing farmers as sensitive towards labor intensive technologies, the same farmers shifted their preference from sole maize (with low labor) to Mbili-Mbili (having high labor) in the 2021 season. Reasons for their change in technology preference included the economic attractiveness of Mbili-Mbili, and its contribution to enrichment of soil fertility through pigeon pea leaf abscission and provision of year-round soil cover that helps to control post-harvest communal grazing, after maize harvesting. Their perception agrees with Chander and Garg (2016) that cropping systems involving species with multiple uses are more preferred by farmers than those with single use because of income diversification, climate resilience and reduced losses from market volatility.

Commodity prices in the market played a significant role in determining preference of crops by the farmers. Pigeon pea prices had been affected by import restrictions imposed to countries with no bilateral agreement with India leading to price dropping from TZS 4,000 before 2015 to TZS 200 in 2017 (Dalton and Regier, 2016). Lifting of the import restriction led to improvement of pigeon pea prices in 2021, which might have led to a corresponding change in perception regarding technology choice by male farmers in Sabilo. Results from our study strongly agrees with those of Kassie *et al.* (2008) that impact of gender of farmer on technology adoption is usually technology specific while the adoption process is location specific.

### ***4.6.3 Household Decision Making as Affected by Introduction of Mbili-Mbili and Doubled-up Legume Technologies***

#### ***4.6.3.1 Socio-economic Characteristics of the Sample***

The participating farmers i.e., survey respondents, were majorly male (71.3%) and 28.7% were female (Table 4.18). Of the farmers who selected to implement Mbili-Mbili trials, 73% were male relative to 57.9% for doubled-up legume. Most of participating households were headed by male members (91.7%) majority of whom had attained up to primary level of education (82.8%). Transition to secondary level of education was higher (19 farmers, 17%) for male than it was for the female respondents (3 farmers, 6.7%). On average, farmer households were composed of 7 members whose main farm managers had 22.6 years of farming experience. No significant differences on farming experience were observed among participants from either male or female-headed households. All farmers involved in this assessment had participated in multiple crop production trainings that were offered by the project. Membership to farmer groups was low (28.2%) despite sensitization on the importance of group formation/joining during the farmer trainings. Participants who implemented Mbili-Mbili trained an average of 4 other farmers while those for Doubled-up legume trained 0.9 farmers ( $p \leq 0.028$ ). Participants who tested Mbili-Mbili indicated willingness to scale up land allocation for the technology by 0.5 ha while those for doubled-up legume indicated 0.3 ha ( $p \leq 0.001$ ).

Table 4.18. Socio-economic characteristics of farmers who tested doubled-up legume and Mbili-Mbili technologies in Babati

Variables and response categories		Technology			Across technology
		Doubled-up legume	<i>Mbili-Mbili</i>	Absolute control	
Gender	<i>Female</i>	16 (42.1)	20 (26.7)	6 (18.8)	45 (28.7)
	<i>Male</i>	22 (57.9)	55 (73.3)	26 (81.3)	112 (71.3)
Headship	<i>Female-headed</i>	3 (7.9)	7 (9.3)	3 (9.4)	13 (8.3)
	<i>Male-headed</i>	35 (92.1)	68 (90.7)	29 (90.6)	144 (91.7)
Age of household head		42.2 ±2.4(31)	45.4 ±1.6(66)	53.1 ±2.8(28)	46.2 ±1.2(136)
Marital status	<i>Married</i>	31 (81.6)	63 (84)	30 (93.8)	136 (86.6)
	<i>Separated /Divorced</i>	1 (2.6)	2 (2.7)	0 (0)	3 (1.9)
	<i>Single</i>	6 (15.8)	10 (13.3)	2 (6.3)	18 (11.5)
Education	<i>None</i>	1 (2.6)	1 (1.3)	3 (9.4)	5 (3.2)
	<i>Primary</i>	32 (84.2)	61 (81.3)	26 (81.3)	130 (82.8)
	<i>Secondary</i>	4 (10.5)	13 (17.3)	3 (9.4)	21 (13.4)
	<i>Tertiary</i>	1 (2.6)	0 (0)	0 (0)	1 (0.6)
Group member	<i>No</i>	29 (78.4)	50 (66.7)	10 (83.3)	89 (71.8)
	<i>Yes</i>	8 (21.6)	25 (33.3)	2 (16.7)	35 (28.2)
Attended trainings	<i>No</i>	23 (60.5)	39 (52)	3 (100)	70 (54.7)
	<i>Yes</i>	15 (39.5)	36 (48)	0 (0)	58 (45.3)
Household size		6.3 ±0.4(38)	6.6 ±0.3(75)	7.7 ±0.5(32)	6.8 ±0.2(157)
Farm size		4.0 ±0.5(38)	5.3 ±0.7(75)	4.6 ±0.6(32)	4.8 ±0.4(157)
Farming experience		19.1 ±2.0(38)	21.7 ±1.6(75)	30.2 ±2.6(32)	22.6 ±1.1(157)

Household headship plays a key role in determining participation of members of a household in agricultural related research. Majority of households in SSA are headed by male figures whose involvement in agronomic research is critical in ensuring uptake of introduced technologies. Male farmers are the dominant decision makers regarding the type of technology to be tested in family land, a condition that could have led to increased participation of men in technology testing process than the female farmers. There are more socio-economic factors favoring male household members (Karanja, 2023) which also increases their advantage in influencing the crops to be cultivated on the family land. For example, male farmers are known to control high value and market-oriented crops such as maize and pigeon pea (Anderson *et al.*, 2021), a factor that might have made their participation in testing Mbili-Mbili to be higher than in doubled-up legume. Their dominance in participatory testing of Mbili-Mbili resulted in willingness to scale the technology in a larger area than that suggested for scaling doubled-up legume (Kinyua *et al.*, 2003). The lower scale area farmers were willing to allocate to doubled-up legume technology which had more women participating (42%) relative to Mbili-Mbili (27%) agrees with Fischer *et al.* (2021) who indicated that men in the study area own 0.7 ha more land than women.

Farmers in the study area had limited sources of knowledge which might have reduced their exposure to agricultural knowledge. This is evident by low transition to secondary education and less participation in farmer groups. If the farmers could access different avenues of knowledge, it would stimulate their learning and increase the implementation of newly emerging technologies resulting in improved crop productivity. Female farmers are more underprivileged regarding access to agronomic information than their male counterparts (Mudege *et al.*, 2017) which can be linked to their low transition to higher levels of education. Venance *et al.* (2016) and McCormack (2018) also reported male farmers as having greater access to agricultural extension services and actively engaging in agricultural related training than their female counterparts.

#### *4.6.3.2 Legume Integration in Fields Under Mbili-Mbili and Doubled-up Legume*

Most (73.5%) of the participating farmers cultivated bean crop on their trial plots compared to their conventional systems (41.6%; Table 4.19). A similar case was observed for pigeon pea where 86.7% of farmers cultivated the crop on trial plots and 73.5% under their conventional practices. Of the farmers who implemented Mbili-Mbili, 60% integrated beans in the system while the crop was cultivated by 97% of farmers who tested doubled-up legume (Table 4.19). The second bean

phase performed well in researcher designed trials however, despite observing this, only 20% for Mbili-Mbili and 14% of households implementing doubled-up legume cultivated two phases of bean. Under Mbili-Mbili trials, pigeon pea was cultivated as an intercrop by 85.3% of households and 89.5% for those implementing doubled-up legume. Ownership of land utilized for testing of the two innovations is predominantly by male farmers (67.6%) however, joint ownership was reported by 18.5% of farmers while only 9.3 of female respondents indicated to have land ownership. Majority of participant farmers (68.1%) established the two innovations under test on moderately fertile fields, though few trials (24.8%) were implemented on fields described to be of low soil fertility.

Table 4.19. Field management operations conducted by farmers who implemented Mbili-Mbili and doubled-up technology in Babati, Tanzania

Variables	Response categories	Technology		Across technology
		Doubled-up legume	Mbili-Mbili	
Planted bean in trial	Yes	37(97.4)	46(61.3)	83(73.5)
	No	1(2.6)	29(38.7)	30(26.5)
Bean phases planted in trial	One phase	32(86.5)	37(80.4)	69(83.1)
	Two phases	5(13.5)	9(19.6)	14(16.9)
Planted bean in conventional system	Yes	21(55.3)	45(60.0)	66(58.4)
	No	17(44.7)	30(40.0)	47(41.6)
Planted pigeon pea in trial	Yes	34(89.5)	64(85.3)	98(86.7)
	No	4(10.5)	11(14.7)	15(13.3)
Planted pigeon pea in conventional system	Yes	34(89.5)	49(65.3)	83(73.5)
	No	4(10.5)	26(34.7)	30(26.5)
Who owns land under technology	Husband	24(64.9)	49(69.0)	73(67.6)
	Wife	4(10.8)	6(8.5)	10(9.3)
	Husband+Wife	5(13.5)	15(21.1)	20(18.5)
	Other HH member	4(10.8)	1(1.4)	5(4.6)
Soil fertility status	Very fertile	2(5.3)	6(8.0)	8(7.1)
	Moderately fertile	26(68.4)	51(68.0)	77(68.1)
	Less fertile	8(21.1)	15(20.0)	23(20.4)
	Infertile	2(5.3)	3(4.0)	5(4.4)
Modified trial design	Yes	7(18.4)	40(53.3)	47(41.6)
	No	31(81.6)	35(46.7)	66(58.4)
Distance of trial plot from homestead (km)		1.3 (± 1.5)	0.9(± 2.1)	na
Number of farmers trained ( $p=0.028$ )		0.9±1.5	4.0±11.9	na
Scale area (ha) ( $p=0.000$ )		0.3±0.3	0.5±0.4	na

For categorical variables, values are arranged as frequencies followed by column percentages in parentheses, na= not applicable, HH = household.

Although a series of trainings on technology design were conducted at the commencement of each of the two seasons of technology trial, 42% of farmers ended up modifying technology design. There was a higher rate of technology adaptation for Mbili-Mbili (53.3%) than doubled-up legume (18.4%; Figure 4.6). Modifications done to Mbili-Mbili included omission of beans (48.6%),

adjusting the number of crop rows (27.1%), omission of pigeon pea (10.8%) and planting other crop species in the system 0.01%). Adaptations on doubled-up legume included introduction of other crop species (57.1%) and omission of pigeon pea (28.6%).

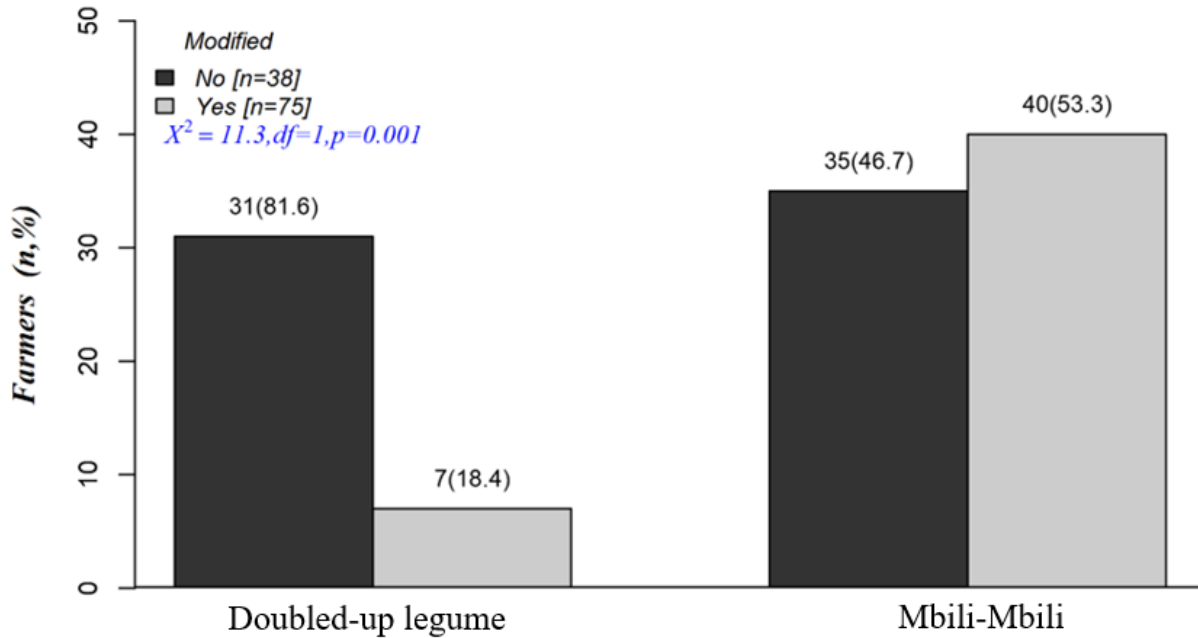


Figure 4.6: Proportions of farmers who modified doubled-up legume and Mbili-Mbili technologies in Babati during the 2020 season. Values outside parenthesis are frequencies, followed by percentages based on response (n).

The fact that bean crop is more sensitive to shading than pigeon pea could be the reason farmers avoided integrating it under their conventional maize-pigeon pea intercropping system. Despite successive trainings and evidence from researcher established trials on good performance of beans under Mbili-Mbili, farmers were more willing to cultivate it under pure legume system (doubled-up legume; 97%) than under maize-legume strip cropping (Mbili-Mbili; 60%). This agrees with Muyanga and Jayne (2006) that farmers with limited resources are conservative to avoid losing their investment. In addition, farmers have accumulated informal knowledge on what may/not work in their systems (Jakku *et al.*, 2019) and takes time before taking up new knowledge that counters what they already know (Cofré-Bravo *et al.*, 2019). This explains why farmers were hesitant to plant two bean phases in a season despite observing a good performance under researcher trial.

In the study area, land ownership is dominated by men which signifies that they have a greater influence and control of crops cultivated therein than their female spouses. However, report on joint land ownership by 18.5% of households, which exceeded the 9.3% by women, is a positive indicator of a transition towards women empowerment through consultative power sharing. In addition, farmers highly valued Mbili-Mbili and doubled-up legume which was evident by their willingness to allocate some land for their implementation. This agrees with Nigussie *et al.* (2017) that farmer allocate land to technologies they adore and consider to be less risky due to the scarce nature of their resources. Not only did allocation of land matter, but allowing implementation of the new technologies on fertile land was an indicator that farmers perceived their potential profitability (Tittonel and Giller, 2013). This also explain why some farmers did not adopt or reject but rather adapted the design of the introduced technologies, an indicator of their willingness to develop while minimizing the levels of risk they could foresee in the researcher's original design (Douthwaite *et al.*, 2001; 2002).

#### *4.6.3.3 Intra-household Decision-making and Resource Control*

Male heads were the main decision makers on majority of field activities conducted in 50-70% of households implementing Mbili-Mbili and 35-65% of households implementing doubled-up legume (Table 4.20). Overall, female participants contributed between 8-25% of decisions relating to Mbili-Mbili and 15-35% for doubled-up legume. There was a higher decision making by female farmers conducting doubled-up legume (at most 36%) than those implementing Mbili-Mbili (at most 25%). In addition, joint decision making was more prevalent in fields where Mbili-Mbili was implemented (10-20%) than for doubled-up legume (3-13%). Differences in decision-making between male and female respondents across different field management activities varied from 16% to 58% for doubled-up legume and from 22% to 62% for Mbili-Mbili. The largest variation in household decision-making relating to field management under doubled-up legume included allocation of land area for technology testing and land preparation at 60% for both practices. The differences were large under Mbili-Mbili (over 40%) than doubled-up legume except for time to harvest beans i.e., 21% of difference. Pest and disease management was conducted by only one farmer in doubled-up legume and 8 under Mbili-Mbili hence excluded from sex-based comparisons. Re-designing of trials was reported by only 7 farmers under doubled-up legume

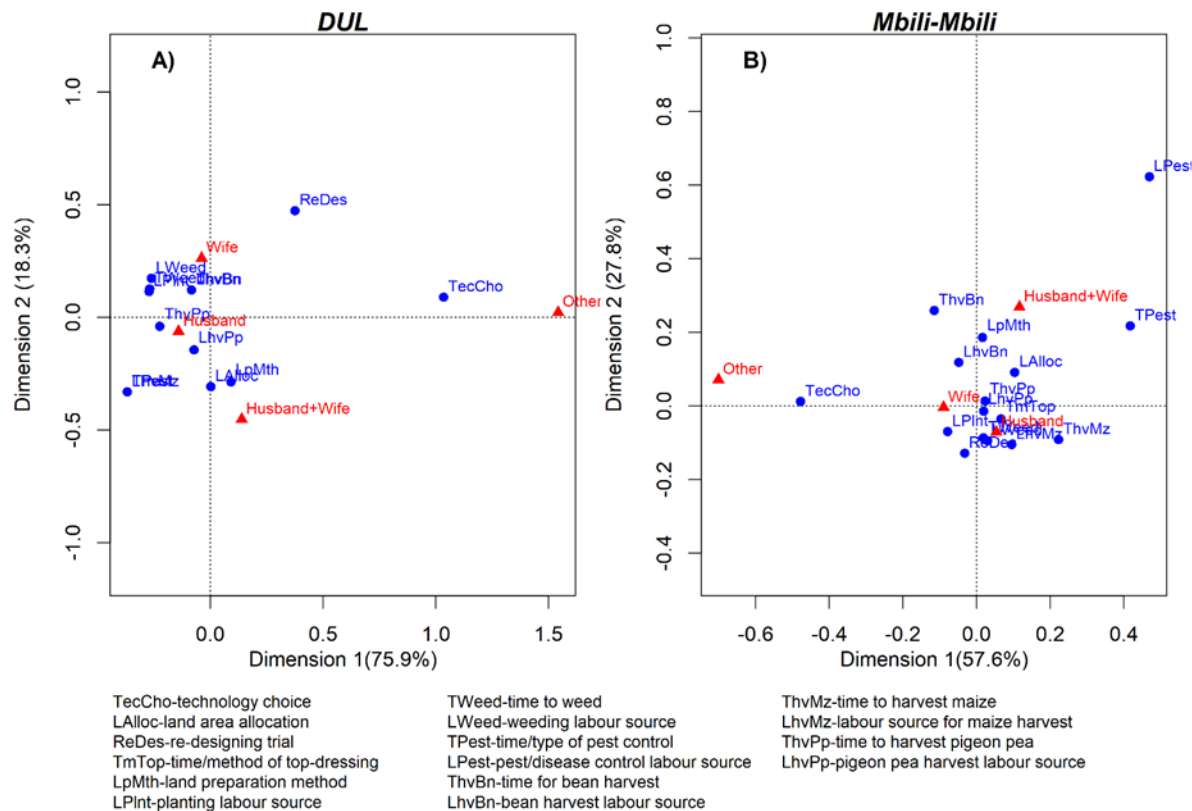
however, 53% of farmers who implemented Mbili-Mbili modified the technology with males having a greater contribution (71%) to the modifications than female (13.2%) farmers.

Table 4.20. Household decision makers for field activities in doubled-up legume and Mbili-Mbili technology in Babati, Tanzania

Decision-making regarding	Doubled-up legume						Mbili-Mbili					
	Husband	Wife	Husband+Wife	Other HH members	Total	Percentage difference (H-W)	Husband	Wife	Husband+Wife	Other HH members	Total	Percentage difference (H-W)
Choice of technology	14 (36.8)	10 (26.3)	3 (7.9)	11 (28.9)	38	10.5	44 (60.3)	10 (13.7)	8 (11.0)	11 (15.1)	73	46.6
Land area allocation	25 (65.8)	6 (15.8)	5 (13.2)	2 (5.3)	38	50.0	49 (67.1)	8 (11.0)	14 (19.2)	2 (2.7)	73	56.1
Time and method of top dressing	-	-	-	-	-	-	38 (70.4)	6 (11.1)	8 (14.8)	2 (3.7)	54	59.3
Land preparation method	25 (65.8)	6 (15.8)	4 (10.5)	3 (7.9)	38 (100)	50.0	47 (64.4)	6 (8.2)	16 (21.9)	4 (5.5)	73 (100)	56.2
Labor source for planting	25 (65.8)	12 (31.6)	1 (2.6)	0 (0.0)	38 (100)	34.2	52 (71.2)	7 (9.6)	9 (12.3)	5 (6.8)	73 (100)	61.6
When to weed	24 (64.9)	12 (32.4)	1 (2.7)	0 (0.0)	37 (100)	32.5	51 (69.9)	10 (13.7)	9 (12.3)	3 (4.1)	73 (100)	56.2
Labor source for weeding	23 (62.2)	13 (35.1)	1 (2.7)	0 (0.0)	37 (100)	27.1	52 (71.2)	9 (12.3)	9 (12.3)	3 (4.1)	73 (100)	58.9
Time to harvest beans	16 (53.3)	11 (36.7)	2 (6.7)	1 (3.3)	30 (100)	16.6	15 (46.9)	8 (25.0)	7 (21.9)	2 (6.3)	32 (100)	21.9
Labor source for harvesting beans	16 (53.3)	11 (36.7)	2 (6.7)	1 (3.3)	30 (100)	16.6	19 (59.4)	5 (15.6)	6 (18.8)	2 (6.3)	32 (100)	43.8
Time to harvest maize	-	-	-	-	-	-	52 (73.2)	8 (11.3)	10 (14.1)	1 (1.4)	71 (100)	61.9
Labor source for harvesting maize	-	-	-	-	-	-	51 (71.8)	9 (12.7)	9 (12.7)	2 (2.8)	71 (100)	59.1
Time to harvest pigeon pea	19 (59.4)	10 (31.3)	3 (9.4)	0 (0.0)	32 (100)	28.1	38 (64.4)	11 (18.6)	9 (15.3)	1 (1.7)	59 (100)	45.8
Labor source for pigeon pea	-	-	-	-	-	-	41 (69.5)	7 (11.9)	9 (15.3)	2 (3.4)	59 (100)	57.6

Values arranged as frequencies and row percentages calculated based on effective responses (in parenthesis). HH represents household, difference (H-W) represents differences between husband and wife.

Correspondence associations between household membership and decision makers for field management practices related to doubled-up legume (Figure 4.7A) and Mbili-Mbili (Figure 4.7B) support the data in Table 4.20. The first dimension accounted for 75.9% and 57.6% of the total variance in decision-making, while the second dimension accounted for 18.3% and 27.8% of the total variance in decision-making patterns for doubled-up legume and Mbili-Mbili trials, respectively.



**Figure 4.7.** Household decision makers on field operations involving implementation of doubled-up legume (A) and Mbili-Mbili (B)

Household headship had a significant contribution on decision making and labor source for the different farm operations. The dominance of male farmers in decision making regarding majority of field operations was observed to be a factor of the crop species being cultivated. High male farmer involvement in decision making related to Mbili-Mbili can be linked to the presence of maize in the system while increased contribution of female farmers in decisions regarding doubled-up legume can be attributed to the presence of beans. Indeed, this study established increment in maize yield of between 50-60% over the farmer practice and upto 0.7 t ha<sup>-1</sup> more bean in doubled-

up legume than Mbili-Mbili which might have played important role in shaping farmer households' technology choices. This agrees with a higher overall stability and profitability (upto US\$ 300) of Mbili-Mbili against doubled-up legume and concurs with farmer behavior as reported in other studies (Kuehne *et al.*, 2017; Snapp *et al.*, 2018) where their technology preference was a function of its profitability. In addition, the ability to access crop production resources, and information on produce market can make male farmers to select systems that are perceived as more profitable than those selected by resource constrained female counterpart (Ambler *et al.*, 2021).

Men dominant control on land and decisions regarding labor allocation was evident during this study. Despite female spouses being involved in decisions on majority of field management practices under doubled-up legume, men had the control over land and labor allocation which could also be an indication of their dominance on diverse production aspects in their households. Land preparation is a masculine task involving use of animal draught and/or tractor drawn plough (Kizito *et al.*, 2022) which could be beyond woman's control. However, female farmers were crucial in making decisions on time for harvesting beans which could partly result from women being the main source of labor (Nakazi *et al.*, 2017; Baudron *et al.*, 2019) or because they are associated with control of bean crop (Njuki *et al.*, 2011). In the study area, bean is considered as a vegetable which makes it to fall under women's domain of overseeing food preparation in the household (Park and White, 2018). Considering that bean was cultivated under small test plots, men would not fight for the control of the crop unlike if cultivated under larger areas where they would sell it to generate income (Njuki *et al.*, 2011; Anderson *et al.*, 2021). Considering that both male and female farmers contribute a significant role in agricultural production and development (Beintema, 2017), there is need to leverage on equal access to agricultural resources.

#### *4.6.3.4 Distribution of Farm Labor Associated with Mbili-Mbili and Doubled-up Legume Across Households*

Male household members were the major source of labor for planting and weeding fields allocated to doubled-up legume and Mbili-Mbili (Table 4.21). Female farmers were the major source of labor for bean harvesting (30-38%), post-harvest bean processing and pigeon pea processing under doubled-up legume technology. Male household heads and their spouses contributed high proportions of farm labor relative to their children.

Table 4.21. Proportions of labour provided by different household members during implementation of doubled-up legume and Mbili-Mbili in Babati, Tanzania

Field activity	Doubled-up Legume				Mbili-Mbili			
	Proportion of labor provided by household members							
	Husband	Wife	Casual	Other	Husband	Wife	Casual	Other
Planting	34.2	27.6	17.1	21.1	39.4	19.4	21.3	20
Weeding	35.7	26.8	12.5	25	38.9	19.1	19.8	22.1
Pest and disease control	57.1	7.1	21.4	14.3	44.7	2.6	42.1	10.5
Bean harvesting	26.7	37.8	13.3	22.2	39.6	32.1	7.5	20.8
Bean post-harvesting	25	35	16.7	23.3	31.3	31.3	7.8	29.7
Pigeon peas harvesting-baby trial	31	31	15.5	22.4	38.5	25.4	13.9	22.1
Pigeon peas harvesting-conventional tillage	28.6	28.6	19.0	23.8	34.3	24.3	21.4	20
Maize harvesting					40.1	22.4	14.3	23.1
Maize harvesting-conventional tillage					34.1	19.7	24.3	22

Introduction of new technologies resulted in significant labor reduction or burden to specific members of farmer households which might have influenced their acceptability for adoption. From the survey, male farmers indicated they had to bear the greatest labor burden during planting and weeding of Mbili-Mbili. However, the reported labor burden by male farmers could be relative because male farmers also take credit of hired labor. This is despite the hiring being conducted using household income that should be accessible to other household members. For example, labor for land preparation is conducted using hired animal/tractor drawn plough in majority of farmer fields (Östberg *et al.*, 2018). Likewise, planting labor in majority of conventional systems is by broadcasting seeds behind own or hired ploughs (Kizito *et al.*, 2022). With Mbili-Mbili requiring additional labor force besides what is provided by the male head (Kinyua *et al.*, 2023), the capital that would be invested in these activities would mainly be generated from crop sales (Coulibaly *et al.*, 2015) which female spouses have also made contribution. For this reason, though female participants reported provision of lower proportions of labor, they might essentially be the major contributors of farm labor (Jakku *et al.*, 2019).

The workload of implementing Mbili-Mbili was reported to be higher than that of conventional systems which could have made farmers to modify the design as a strategy of moderating its labor demands. Increased labor, optimization of incomes and food security were cited as other major reasons for modifying initial design of Mbili-Mbili technology. Kalinda (2014) and Jones *et al.* (2012) reported that male farmers are more often responsible for farm activities that are resource-intensive or those that required physical strength. However, female farmers are more often involved in strenuous and health threatening tasks (Majumder and Shah, 2017). Indeed, post-harvesting activities involving legume crops, especially winnowing dusty grain is mainly conducted by women and children (Badodiya *et al.*, 2016). The process generates fine particulate organic matter which could affect women/children if exposed for longer periods. Contrastingly, men take up roles that are lighter such as threshing of produce where labor-saving machines are involved. In mechanized scenarios, women and children only come in to substituted men (Pingali, 2007).

#### *4.6.3.5 Decisions on Produce Marketing and Control of Associated Income*

Household decisions relating to produce marketing and control of derived income was mainly dominated by male members. Male dominance in produce marketing and control of the associated

income spanned from establishing the proportions of produce to be sold. Male farmers were quick to sell crop produce a short period after harvesting relative to their female counterparts. Up to 90% of male-headed households sold produce from all component crops i.e., maize, beans, and pigeon pea. Male farmers sold 67% and 69% more pigeon pea grain cultivated under doubled-up legume and Mbili-Mbili systems, respectively, and 14% more maize in Mbili-Mbili than female farmers. For the bean component male farmers sold 100% of yields from Mbili-Mbili. Decisions on control of incomes were made by male household heads (42%), followed by a joint decision by male + female spouses (29.5%), female spouses (22.2%) and other household members (7%; Figure 4.8A). The correspondence biplot between household membership and income control from crop sale showed that male household heads and joint male + female spouses had strong association (84.9% of variance) in decision-making related to their household income. The two categories of farmers had control over incomes generated from sale of maize and pigeon pea while female spouses were associated with decisions relating to control of incomes generated from sale of bean (15.1% of variance; Figure 4.8B).

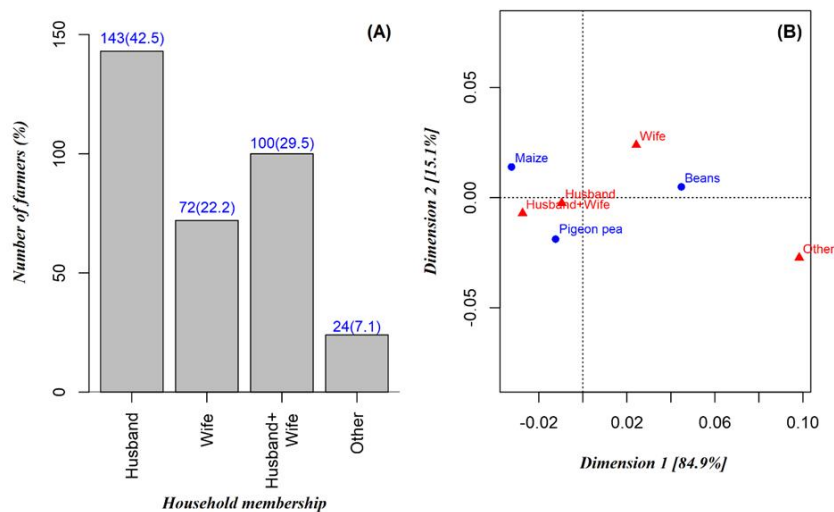


Figure 4.8. Gender structured decision-making regarding control of income generated from crop sales during the 2020 season in Babati (A) and associations between decision-makers on control of household income from different crop enterprises (B).

The gender role of shaping social norms, status and relations strongly emerged on decisions relating to control of produce market and associated incomes. Majority of participating farmer households were patrilineal where male heads have the responsibility of providing for their families. However, male involvement in making quick sale of harvested produce and their

dominance in establishing proportions of produce to sell may have a negative influence on the food security for their households. It was evident that female participants were more sensitive to produce sale than their male counterpart who reportedly sold more than 65% of legume. This is an indication that women were more cautious in ensuring that their households are food secure than the men (Carr, 2008) In addition, men had more right of access and control of household resources (including food) than the women (Perez *et al.*, 2015). To men, food security could be defined as availability of maize for consumption by the household while women may focus on a more balanced nutrition that integrates legume in the diet (Nchanji *et al.*, 2021) hence the observed differences in proportions of crop sales. This could be the reason Gough (2007) described men as naïve and vulnerable to diet and women as nutritional experts.

Despite being referenced as a woman crop, beans have a stable market which often triples the prices derived from maize sale which could be the reason why men targeted its sale than they did for maize. Observations from this study indicated a probability for men taking control over any crop that has promisingly high income regardless of the value it has in the household diet. This agrees with Ngoma-Kasanda and Sichilima (2016) on reduced female control over produce sales when net benefits from a crop accounted for a large share of the household total income. For this reason, decisions by male and female household members are heterogeneous because preferences by men are not necessarily the relevant determinants of households' resource allocation (Bellon *et al.*, 2006; Sulo *et al.*, 2012).

The existence of a strong association on income related decisions by male heads, and in some cases jointly with their female spouses, could indicate male dominance even when decisions are jointly discussed. Despite being an important source of farm labor, women seemed to be exempted from participating in decisions relating to use and control of agricultural-derived incomes. This agrees with Peralta (2022) who cited female participation in numerous production aspects involving food and cash crops despite a reduced control and autonomy over generated resources. Mirjana *et al.* (2020) associated the limited contribution of women in access and control over financial resources with lower education levels and discriminating cultural norms. It is important to recognize that ownership, access to, and control over agricultural resources constitute critical elements of an improved household welfare which women forms part (Pelekamoyo and Umar, 2019).

### *Hypothesis testing*

**H<sub>0</sub>:** The gender of farmer does not influence agricultural decisions on implementing improved cropping systems.

Results of this study indicate that the gender of farmer has a significant influence on the different crop management decisions. Under the conditions of this study, male farmers dominate in making decisions relating to maize and pigeon pea production while women make decisions relating to beans, thus allowing the rejection of the null hypothesis.

## **4.7 To Examine How Different Socio-Economic Factors Affecting Farmer Knowledge on Implementing Improved Cropping Systems**

### ***4.7.1 Socio-demographic Characteristics of Farmers Participating in Assessment of Knowledge Relating to Implementation of Mbili-Mbili and Doubled-up Legume***

Male household head were the dominant (64.3%) category of farmers participating in the study followed by spouses (30%) and children (5.7%; Table 4.22), with male farmers being 62.9% across the three categories. About 84.3% of participating farmers had attained primary level while the rest had secondary level of education. Only 47.3% of participants were full-time farmers earning an average of US\$ 1060 from crop production while the rest were involved in other income generating activities which provides an additional income of US\$200 per year. Group membership was reported by 21.4%, 66.7% of whom came from Gallapo village. Farmers indicated ownership of an average of 4.2 acres of land with 3.6 acres being utilized for crop cultivation. Manure was reported as the main source of plant nutrient for 50.7% while only 12.9% indicated to have applied inorganic fertilizers in their fields.

Table 4.22. Socio-demographic characteristics of farmers participating in agronomic knowledge assessment study during the 2020 season in Babati

Parameters		Gallapo	Riroda	Sabilo	Total
		Number of participants (n)			
Status in household	Household head (1)	71.1 (32)	69.6 (32)	53.1 (26)	
	Spouse (0)	28.9 (13)	28.3 (13)	32.7 (16)	
	Child (0)	0 (0)	2.2 (1)	14.3 (7)	
Sex of respondent	Male (1)	64.4(29)	65.2 (30)	59.2 (29)	
	Female (0)	35.5 (16)	34.8 (16)	40.8 (20)	
Marital status	Married (1)	86.7 (39)	89.1 (41)	75.5 (37)	
	Single (0)	13.3 (6)	10.9 (5)	24.5 (12)	
	None (0)	2.2 (1)	0 (0)	2.2 (1)	
Education	Primary (0)	82.2 (37)	87.0 (40)	83.7 (41)	
	Secondary (1)	15.5 (7)	13.0 (6)	14.3 (7)	
Group member	No	55.5 (25)	89.1 (41)	89.8 (44)	
	Yes	44.4 (20)	10.9 (5)	10.2 (5)	
Fertilizer use	No	88.9 (40)	89.1 (41)	83.7 (41)	
	Yes	11.1 (5)	10.9 (5)	16.3 (8)	
Manure use	No	62.2(28)	58.7 (27)	31.1 (14)	
	Yes	37.8 (17)	41.3 (19)	68.9 (35)	
Farming engagement	Full-time (1)	44.4(20)	58.7 (27)	73.5 (36)	
	Part-time (0)	55.5(25)	41.3 (19)	26.5 (13)	
Age		44.6±12.9(45)	41.8±13.2(46)	42.7±13.9(49)	43.0±13.3(140)
Land area (acres)		5.1±5.8(45)	3.4±2.2(46)	4.0±3.5(49)	4.2±4.1(140)
Cultivated farm size (acre)		3.8±3.9(45)	3.4±3.1(46)	3.4±2.2(49)	3.6±3.2(140)
Farming experience (years)		21.4±13.7(45)	21.0±13.9(46)	20.1±13.2(49)	20.8±13.5(140)
Technology land area (acres)		0.3±0.1(45)	0.3±0.1(46)	0.3±0.04(49)	0.3±0.1(140)

Distance from homestead (km)	0.8±1.0(45)	1.0±1.4(46)	0.6±0.7(49)	0.8±1.1(140)
Labor demand (man days)	2.3±0.7(45)	2.2±0.3(46)	2.4±0.7(49)	2.3±0.6(140)
Maize equivalent yield (t/ha)	1.1±0.8(45)	0.7±0.5(46)	1.0±0.7(49)	0.9±0.7(140)
Household size	6.6±2.8(40)	5.9±2.5(34)	6.1±2.2(37)	6.2±2.5(111)
Dependency ratio	1.3±1.0(40)	1.1±0.8(34)	1.5±1.3(37)	1.3±1.1(111)
Livestock income (USD yr <sup>-1</sup> )	206.6±380.9(40)	160.0±287.0(34)	50.0±136.3(37)	140.1±294.4(111)
Off-farm income (USD yr <sup>-1</sup> )	161.1±247.7(40)	372.2±769.8(34)	131.0±426.9(37)	215.7±519.9(111)
Crop income (USD yr <sup>-1</sup> )	827.1±1,253.8(40)	1,539.6±4,072.4(34)	884.5±1,143.1(37)	1,064.5±2,462.0(111)
Agriculture income (USD yr <sup>-1</sup> )	1,033.7±1,517.3(40)	1,699.6±4,059.4(34)	934.5±1,179.2(37)	1,204.6±2,515.1(111)
TLU	3.5±4.1(40)	2.4±3.8(34)	5.0±3.5(36)	3.7±3.9(110)

*Categorical variables: Values are arranged as the number of farmers (in parenthesis) and column percentages. Numeric variables: Values are arranged as means, ± standard deviations, and number of farmers (in parenthesis). TLU refers to Tropical Livestock Units.*

The influence of gender on land use and control was visible during the farmer knowledge assessment where majority of the participants were male household heads. Farmer households in Babati Tanzania and majority of Eastern African region are patrilineal with male household heads being the major decision makers on operations involving use of their land (Peterman *et al.*, 2011). During the introduction of the new technologies, men were eager to examine and approve the design and nature of crops to be tested on their land. Their approval was pegged on one condition, that the new technology did not affect the yield of maize. The study attributes lower participation of female farmers in technology testing to their limited power of access and use of family land, mostly under the control of male spouses (Lusasi and Mwaseba, 2020). This is based on findings by Fischer *et al.* (2018) who indicated women as owning an average of 0.7 ha lesser land than men. In addition, Kapsler *et al.* (2021) indicated that female farmers are more risk averse to adoption of new technologies relative to men. In this regard, increase in participation of female farmers could be expected after the introduced technology has been endorsed by their male colleagues.

The power over land ownership and the highest level of education attained had a significant influence on women's role and their ability to make decisions pertaining to crop production. As earlier indicated, it is documented that men own more land than women (Matere *et al.*, 2022). This makes the crops being cultivated, especially if grown for sale in local markets, to be under control of male household heads (Me-Nsope *et al.*, 2015). Men are also the sole decision makers on what crop to sell, the amount, when, where at what price and how the proceeds from produce sale are to be utilized (Me-Nsope and Larkins 2015, 2016). Another factor of importance is the role cultural norms and education plays in limiting the involvement of female farmers in decision making (Huang *et al.*, 2021). Female farmers may feel inferior and excluded on farming decisions that largely affect them (Theis *et al.*, 2018). To optimize crop production in the current times of increased climate vulnerability, there is need to ensure agronomic innovations being developed are gender sensitive (Meinzen-Dick *et al.*, 2014) and to sensitize on inclusion of female farmers in agricultural-based decision making (Kabir *et al.*, 2019) considering their key role in provision of the necessary farm labor.

The fact that 52% of farmers in the area indicated that they are actively involved in informal business to supplement their agricultural derived incomes shows the role of climate change in

shaping the diversity of sources of income for smallholder farmers. As uncertainties in crop production continue to increase, farmers tend to seek other income generating activities to increase their resilience. Limited financial capital has been a major challenge facing smallholder farming households causing a '*distress push*' towards seeking cash income from other off-farm activities (Babatunde *et al.*, 2010). With the right policies, farmers can be assisted to complement their on-farm incomes with off-farm activities as an insurance, or income diversification strategy, against weather associated risks and scarce arable land (Ellis and Freeman, 2004).

#### ***4.7.2 Farmers' Rating of Training, Individual Knowledge, and Extent of Technology Adoption***

Farmers indicated that training sessions conducted on the different sustainable intensification themes relating to implementation of Mbili-Mbili and doubled-up legume technologies were very effective (mean 4.3; Table 4.23). They rated their own knowledge above average (mean 3.8) and indicated the extent of using the sustainable intensification technologies as moderate (mean 3.3). Farmer knowledge on some technologies like proper pest and diseases control was between average ( $\geq 3.4$ ) and high on use of certified seeds (4.2) however, extent of uptake of these technologies was reported to be low (2.3). Knowledge on use of certain technologies whose utilization by farmers has been promoted for a longer period e.g., certified seeds (4.2) were directly proportional to extent of their utilization (4.6). Implementation of technologies that were recently introduced by the project in the study area i.e., Mbili-Mbili and doubled-up legume, and ISFM practices like use of inorganic fertilizers had low extent of use by farmers (mean 2.3). Despite indicating to have knowledge on good agricultural practices such as proper spacing and soil and water conservation, application of this knowledge in their crop fields was low (mean utilization score of 2.8 and 2.9, respectively).

Table 4.23. Farmer knowledge scores on different sustainable intensification themes introduced at different span of time in Babati

Indicators	Project training effectiveness	Value of training offered	Knowledge rating	Extent of using New Technology
Using certified seeds <sup>β</sup>	4.5(0.69)	4.8(0.55)	4.2(0.92)	4.6(0.87)
Pest and disease control <sup>β</sup>	4.2(0.97)	4.6(0.74)	3.4(1.21)	3.2(1.26)
Proper crop spacing <sup>β</sup>	4.4(0.72)	4.7(0.67)	4.0(0.93)	2.8(1.34)
Timely planting <sup>β</sup>	4.3(0.85)	4.7(0.64)	4.0(0.94)	4.0(1.23)
Fertilizer use <sup>β</sup>	4.3(0.94)	4.5(0.83)	3.6(1.15)	2.3(1.13)
Soil and water conservation <sup>π</sup>	4.3(0.95)	4.6(0.80)	3.6(1.12)	2.9(1.24)
Manure use <sup>π</sup>	4.1(1.04)	4.6(0.74)	3.8(1.07)	3.6(1.15)
Implementation of Mbili-Mbili and doubled-up legume <sup>ε</sup>	4.4(0.74)	4.8(0.48)	3.7(0.83)	2.3(1.24)
Total	4.3(0.88)	4.7(0.68)	3.8(1.06)	3.3(1.41)
Significance	**	**	***	***

<sup>ε</sup>Represents interventions introduced in 1980s, <sup>π</sup> those introduced in 1990s, and <sup>ε</sup> interventions explicitly introduced during the current study. In all cases, the minimum score signifying low knowledge was 1 and maximum score signifying high knowledge was 5, values in parenthesis are standard deviation across means, \*\*\*Significant at 0.01 probability level, \*\*Significant at 0.05 probability level and \* Significant at 0.1 probability level.

Participant farmers were likely to acquire and apply knowledge aspects that are easy to decode, and which unravel crop production challenges they can associate with. The vulnerability of smallholder farming systems to unpredictable weather conditions might have triggered farmers' interest to acquire knowledge that increase their climate-resilience i.e., timely planting, using quality seeds, and timely management of pest and diseases. Farmers also have a strong drive towards achieving a climate resilient state with reduced loss of yield for not utilizing good agricultural practices that could have pushed them to seek and utilize the functional agronomic

knowledge. Shiferaw *et al.* (2014) indicated that farmers normally prepare for climate related shocks by ensuring a quick adoption of risk management strategies *ex ante*. For example, elderly farmers who played critical role of decision making in Babati were skeptical of utilizing certified maize seeds in 1990's citing unpleasant taste, vulnerability to pest attack and unsuitability to local weather (Snyder *et al.*, 1996). This situation has changed over time with Kihara *et al.* (2015a) reporting only 14% of farmers were planting local/recycled/mixed maize varieties.

Farmers acknowledged they had received effective training for both Mbili-Mbili and doubled-up legume technology and that associated knowledge added value to their crop production. However, they were rigid to scale up the two innovations. With continuous sensitization, farmers have slowly accommodated change and uncertainties associated with new innovations which may help to enhance their resilience (Folke, 2010). Availability of capital to invest on new farming methods such as mechanization (Sewando *et al.*, 2016) may increase the risk aversiveness of farmers and reduce their likelihood to invest in labor intensive innovations like Mbili-Mbili. In such a scenario, farmers with limited resources would tend to “exhibit a wait-and-see mentality” (Muyanga and Jayne, 2006) and end-up not adopting the technology.

#### ***4.7.3 Knowledge Scores for Mbili-Mbili, Doubled-up Legume and Associated Agronomic Practices***

The knowledge score for participant farmers implementing Mbili-Mbili and those for doubled-up legume revealed different patterns. For implementors of Mbili-Mbili, knowledge scores relating to ‘Certified seeds increase yields, Timely pest and disease management, Pigeon pea providing year-round cover, Rotation altering pest and disease cycles, Pigeon pea roots breaking hard pans, the same roots controlling soil erosion, Mbili-Mbili reducing shading on legumes, offering more food secure months, and being more risk averse than conventional intercropping’ had a mean above 4.5 (Table 4.24). Contrastingly, these same farmers had low scores (<3.7) on knowledge regarding ‘Topdressing fertilizer required for maize even when basal fertilizer was not applied, combining fertilizers and manure as plant nutrient source, Alternation of legume crop rows with those of maize, planting a second phase of bean after harvesting the first crop, Need for basal fertilizer application despite plans to top-dress, and Mbili-Mbili accommodating equal number of plants as conventional systems’. Higher knowledge scores were recorded for general agronomic and application aspects relating to Mbili-Mbili despite limited knowledge on both the explicit

management aspects such as fertilizer and manure application, and technical aspects involving design of Mbili-Mbili.

For implementors of doubled-up legume, high scores (i.e., means  $>4.5$ ) were recorded on constructs involving ‘Timely planting and utilization of certified seeds enhancing crop yields, timely pest and disease management, Abscised pigeon pea leaves improving soil fertility, Pigeon pea root network controlling soil erosion and breaking hard pans, the dense canopy providing soil cover’ and ‘conducting crop rotation helping to manage pest and diseases’. Low knowledge scores (means  $<3.5$ ) were recorded on constructs involving ‘Post-harvest grazing on crop fields compacting and destroying soil structure, arrangement of legume rows, and increasing the system’ legume production through planting two in-season bean phases’.

Table 4.24. Mean knowledge scores for agronomic aspects around Mbili-Mbili and doubled-up legume

Knowledge items	Mbili-Mbili	Doubled up legume
Timely pest controls yield loss	4.81(0.40)	4.69(0.51)
Certified seeds improve crop yields	4.73(0.64)	4.82(0.48)
Pigeon pea provides year-round soil cover	4.71(0.55)	4.57(0.67)
Timey planting optimizes moisture use	4.71(0.59)	4.84(0.42)
Rotation breaks disease cycle	4.69(0.58)	4.55(0.71)
Pigeon pea rooting prevents erosion	4.66(0.64)	4.63(0.63)
Pigeon pea roots break hard pans	4.65(0.64)	4.57(0.76)
Technology reduces shading of legumes	4.62(0.59)	4.26(0.48)
Technology increase food secure months	4.57(0.66)	4.28(0.45)
Technology is risk aversive than conventional	4.55(0.81)	4.26(0.48)
Proper spacing achieves right plant population	4.10(1.05)	3.63(1.23)
Abscised pigeon pea leaves improve soil fertility	3.94(0.96)	4.65(0.56)
Technology involves planting two species of legume	3.52(1.07)	2.12(1.42)
Fertilizer and manure can be combined	2.34(1.13)	3.59(1.02)
Two bean phases are feasible in a season	2.63(1.48)	2.8(1.5)
Technology reduces competition for growth resources	3.54(0.99)	
Technology has equal maize rows as conventional	3.27(1.26)	
Legumes planted adjacent to double maize rows	2.48(1.48)	
Basal fertilizer used despite plans for top-dressing	2.65(1.2)	
Top-dressing done whether basal fertilizer is applied	2.19(1.08)	
Rotation beneficial to cereal-based systems		4.20(0.53)
Pigeon pea improves fertility of soil		4.18(0.59)
Pigeon pea and beans can be planted concurrently		4.08(0.83)
Technology prevents post-harvest grazing on crop fields		4.18(0.62)
Grazing livestock on field compacts soil		1.62(0.94)

*Values represent mean knowledge score of different constructs while in parenthesis are the standard deviation of mean.*

The ability to decipher knowledge on different aspects of agronomic innovations were not directly related to the time when the different technologies was introduced to farmers, but variation existed for each unique innovation. During this study, farmers rated both their level of knowledge and the

extent they had been using some interventions introduced in 2018 like those introduced in early 1980s. Indeed, farmers may easily decipher knowledge on certain agronomic aspects more than others. However, there is low adoption of ISFM practices such as inorganic fertilizers that are important in bridging the existing yield gap. Though low, inorganic fertilizer utilization of 13% during this study agrees with the 15% use reported by Mponela *et al.* (2023) which is a significant improvement from the 3% reported by Adu-Gyamfi *et al.* (2007). Kihara *et al.* (2015a) also indicated that maize yields in smallholder systems of Babati and elsewhere in SSA have stagnated at 2 t ha<sup>-1</sup> despite a potential of attaining 7.5 t ha<sup>-1</sup>. Despite a 50.7% use of organic manure reported in this study and 60% by Mponela *et al.* (2023), farmers sensitization on the importance of complementing manure with inorganic fertilizers to unlock crop yields is critical.

#### ***4.7.4 Farmer Knowledge Structure of Sustainable Intensification Technologies***

Multinomial analysis explained 71.7% of variation in knowledge regarding the 20 constructs on Mbili-Mbili (Table 4.25; Figure 4.9A). Four components were generated with the first having high loadings on ‘*functional knowledge*’ relating to good agricultural practices (GAPs) i.e., timely pest and disease management (Mb12), deep rooted pigeon pea crop helping to break hard pans (Mb8), use of certified seeds enhancing yield (Mb1), rotations involving different crop species altering pest and disease cycles (Mb11), the dense pigeon pea canopy of pigeon pea providing soil cover (Mb9), while their rich network of roots controlling soil erosion (Mb10), need for timely planting to optimize soil moisture utilization (Mb3), and need for maintaining proper plant spacing (Mb2). Second component was related to ‘*technical knowledge*’ on aspects around Mbili-Mbili due to high loadings on Mbili-Mbili design like arrangement of three intercrop components (Mb13), legumes arrangement adjacent the double maize rows (Mb14), system’s ability to accommodate two bean phases in a season (Mb16) and achieving equal maize population as properly spaced conventional system (Mb15). Overall, there was a distinct negative association of both the functional and technical knowledge themes (Figure 4.8a).

The third component involved constructs that explained farmer knowledge on ‘*applicability*’ of benefits associated with Mbili-Mbili. The component had high loading of aspects such as Mbili-Mbili enhancing light penetration to intercropped legumes (Mb18), the system being risk averse (Mb19), providing more food secure months (Mb20) and reducing interspecific competition for growth resources among intercrop components relative to conventional systems (Mb17). The last

component was related to '*soil fertility*' aspects with high loadings for topdressing maize being critical regardless of basal fertilizer being applied (Mb5), combining inorganic fertilizers and manure as a source of plant nutrients (Mb6), and abscised pigeon pea leaves enhancing soil fertility (Mb7). There was a positive association between farmers having functional knowledge and being able to apply knowledge on ISFM practices.

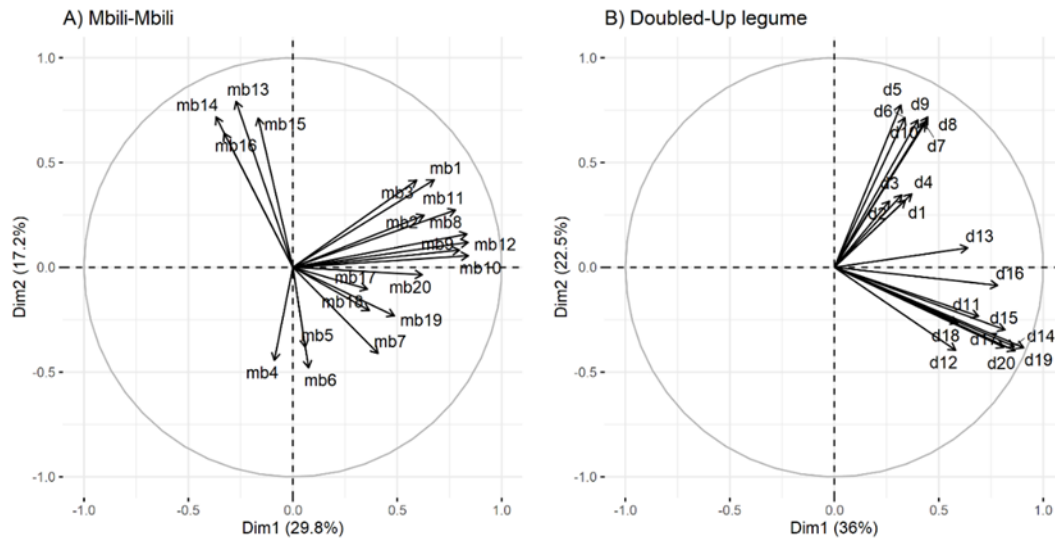
Table 4.25. Rotated component matrix of constructs assessing farmer knowledge on Mbili-Mbili and doubled-up legume technology in Babati, Tanzania

Mbili -Mbili knowledge items	Mbili-Mbili			Comm.	Doubled-up Legume				Comm.
	Func.	Tech.	Appl.	Soil fert.	Func1.	Func2.	Appl.	Soil fert.	
Certified seeds improve crop yields	0.83				0.72	0.92			0.88
Timely planting optimizes moisture use	0.72				0.56	0.9			0.85
Proper spacing ensure plant population	0.7				0.54	0.85			0.754
Pigeon pea canopy provides soil cover	0.77				0.66		0.74		0.66
Pigeon pea network of roots control erosion	0.75				0.71		0.88		0.79
Pigeon pea roots break hard pans	0.84				0.75		0.88		0.79
Rotation alters disease cycle	0.81				0.69		0.83		0.74
Timely pest management reduce yield loss	0.86				0.78		0.86		0.77
Pigeon pea litter enhance soil fertility				0.46	0.56		0.83		0.72
Technology increase food secure months			0.78		0.73			0.98	0.98

Technology is risk averse than conventional	0.89	0.82	0.95	0.91
Technology reduces shading of legumes	0.89	0.79	0.95	0.91
Integrates two legume species	0.94	0.89	0.66	0.61
Fertilizer and manure can be combined		0.9	0.82	0.8
Accommodates two bean phases	0.86	0.75	0.73	0.76
Legumes planted adjacent two maize rows	0.88	0.8		
Same maize rows as conventional	0.77	0.64		
Reduces competition for growth resources	0.67	0.49		
Basal fertilizer needed despite top-dressing		0.88	0.8	
Top-dress whether basal fertilizer was applied		0.92	0.86	
Post-harvest grazing on field compacts soil			0.88	0.82
Technology keeps livestock off the fields			0.66	0.53
Pigeon pea and beans can be sown same day			0.69	0.52

Pigeon pea improves soil fertility							0.85	0.77	
Cereal-legume rotation is beneficial							0.79	0.79	
<b>Eigen values</b>	6.0	3.4	2.6	2.3		2.4	4.5	7.2	1.2
<b>Percentage of variance (%)</b>	29.8	17.2	13.1	11.7		12	22.6	36.1	5.9
<b>Cumulative variance (%)</b>	29.8	47	60.1	71.7		12	34.6	70.7	76.5

*KMO measure of sampling adequacy =0.766 and 0.752, Bartlett's test of sphericity (Chi-square=0.766 and 0.942 in Mbili-Mbili and doubled-up legume, respectively, df=190, Significance=0.000). Func. represents functional knowledge on good agricultural practices, Fuct1. represents functional knowledge relating to crop establishment and yield optimization, Func2. represents functional knowledge relating to soil, pest and disease management, Tech. is technical knowledge, Soil fert. is soil fertility knowledge, Appl. is application knowledge. Comm represents communality.*



**Figure 4.9.** Principal component analysis biplots of sustainable intensification innovations indicating the association between knowledge items for farmers who implemented Mbili-Mbili (A) and doubled-up legume (B) technologies in Babati. Values in brackets are variances explained by items in component 1 and 2 of the multivariate model.

Multinomial analysis on knowledge scores of farmers participating in implementing doubled-up legume explained 76.5% of variation in their knowledge. Four components explaining farmer knowledge on doubled-up legume were grouped into one dimension (i.e., Dim 1, Figure 4.9B) implying positive association amongst these knowledge components. First component had loading on constructs relating to ‘functional’ knowledge on aspects involving crop establishment and yield enhancement. It had high loadings for using certified seeds enhances crop yields (D1), planting should be done at rainfall onset to optimize on moisture (D3), proper spacing increases plant density relative to broadcasting seeds behind plough (D2). The second component was categorized as ‘functional’ knowledge on aspects involving *management of soil and pest and diseases* and had high loading for the deep-rooted pigeon pea breaking hard pans (D6), the rich root network preventing erosion (D8), need for timely management of pests and diseases to avert yield loss (D10) and leaf abscission improving soil fertility (D5). Component relating to ‘Application’ aspects were third. The associated aspects include doubled-up legume assuring more food secure months than bean monocultures (D19), the system being risk

aversive than bean monoculture systems (D20), pigeon pea not shading intercropped beans (D14), soil compaction through post-harvest grazing destroying soil structure (D17), ability of pigeon pea crop to improve soil fertility (D15) and the system accommodating two in-season bean phases (D13). Component regarding integration of inorganic fertilizer and manure (D4) was categorized under ‘*soil fertility*’ theme.

The ease of acquiring and decoding both the functional and application knowledge varied from that of technical knowledge among farmers conducting Mbili-Mbili innovation. Contrary, a strong positive relationship was observed for constructs relating to functional and application knowledge among farmers conducting doubled-up legume. The emerging patterns of knowledge on the new innovations during this study can guide future rollout of these technologies to farmers in other regions. For example, functional and application aspects that are easy to decipher by farmers i.e., use of quality seeds, considering proper spacing, and information on benefits accrued from the different component crops, can be presented concurrently when rolling out Mbili-Mbili. However, the functional and application aspects should be separated from technical knowledge (Jambo *et al.*, 2019) involving its intercropping design. This is considering farmers take more time to decipher and apply the technical aspect of Mbili-Mbili (Mucheru-Muna *et al.*, 2021). Researchers, extension staff, and other agricultural practitioners should also employ different training approaches while rolling out diverse agronomic interventions to smallholder farmers because their understanding by farmers differs for each unique technology (Greenhalgh *et al.*, 2005).

Participation in series of training and implementation of agronomic technologies did not guarantee increased farmer knowledge on the same technologies. During this study, farmers participated in 2-years of intensive training but had limited knowledge on proper design of Mbili-Mbili innovation. Establishment of Mbili-Mbili technology requires precision on design and is more labor intensive than their business usual system which contributed to slow acquisition of associated knowledge. The need to shift their mindset from broadcasting seeds behind ploughs (Kizito *et al.*, 2022) to intensive labor and increased precision at planting (Kinyua *et al.*, 2023) can cause farmers to strongly hold

onto their local practices. This is because farmers may take time to appreciate a different innovation whose operations demand a different strategy from their usual management practices (Martínez-García *et al.*, 2013).

The aspect of farmers having limited knowledge on ensuring proper spacing is not unique in the study area. Usually, farmers broadcast different seed varieties in the plough-line generated by animal and/or tractor drawn ploughs. The broadcasted seeds may be deeply buried resulting in low germination percentage, sometimes <24,000 plants ha<sup>-1</sup> for maize, with less than 20% of farmlands attaining the required plant population of 53,000 plants ha<sup>-1</sup> for maize (Mugi-Ngega *et al.*, 2021; Kihara *et al.*, 2015a). Despite the current maize density being less than half of the required, it is better than the 15 seeds sown per planting station at an intra-row spacing of 2 feet reported in the same area by Snyder *et al.* (1996). This shows that acquisition and application of technical agronomic innovations could be slow, knowledge-intensive, and may require farmers to unpack some of their local practices and substitute them with improved practices. The unlearning/ relearning process require proper facilitation so that it does not conflict with farmers' informal knowledge. This can be achieved through intensive training and rigorous involvement in technology testing process (Tchuwa *et al.*, 2022).

The fact that access to farm inputs such as fertilizers is capital-intensive might have been a dis-incentive on their utilization by farmers affecting the acquisition and scaling of related knowledge. This can explain why they had a low score on knowledge and extent of using inorganic fertilizers and manure either as sole or in combined form. The problem with access to fertilizer input might have contributed to a local myth by farmers in the area who associate inorganic fertilizers with '*destroying the soil*' (Snyder *et al.*, 2020). This could be the reason IFDC (2012) and Mponela *et al.* (2023) reported fertilizer application rates of <10% for foliar and <15% for basal applications.

Only half of farmers have reported positive adoption of organic manure in the study area. This can be one of the major contributors of existence of yield gap in smallholder farmer fields. Even for farmers applying manure, its application is mostly haphazard with varying

quantities and application methods. Inadequate resources to prepare enough manure for applying in the whole farm, the bulky nature of manure during transportation and intensive labor required for application might also contribute to its average (~ 60%; Kome *et al.*, 2018; Mponela *et al.*, 2023) rate of adoption. Sustainable fertilizer input support programs (including training) have been promoted to improve use, availability, and accessibility of fertilizers by resource-poor farmers (Jayne *et al.*, 2018; Holden, 2019). In addition, promotion of legume-based innovations like Mbili-Mbili and doubled-up legume over cereal monoculture systems can improve biological fixation of nitrogen (Chikowo *et al.*, 2020). This can help to reduce farmer dependency on the expensive inorganic fertilizer inputs (Behnassi and El Haiba, 2022).

Accessibility to cheaper plant nutrient sources such as manure may be hindered by declining pastoral lands that affects local methods of livestock rearing. Increasing the awareness on benefits accrued from combining manure and inorganic fertilizer can improve farmer knowledge on the benefits conceived when the two inputs are integrated and boost crop yields (Vanlauwe *et al.*, 2011; Ejigu *et al.*, 2021). Low farmer knowledge on benefits of integrating inorganic fertilizers and manure on the same plot are consistent with Mugi-Ngega *et al.* (2021), who reported only 29% of farmers in Babati combine manure and inorganic fertilizers. Farmers also had knowledge on cheaper and locally available alternatives of plant nutrient sources like residues from abscised pigeon pea leaves. This could be because pigeon pea leaf abscission is a free ecosystem service for farmers who plant the crop and does not require transportation labor like farmyard manure. Sakala (1994) established that abscission of pigeon pea leaves contributes between 75–95 kg N ha<sup>-1</sup>. Our assertions agree with Tchuwa *et al.* (2022) who reported that mixing of different soil health options is a strategy that can be applied by resource poor farmers as a substitute for unaffordable agricultural inputs.

Farmers appreciated pigeon pea integration in Mbili-Mbili and doubled-up legume control the post-harvest grazing which is rampant in the area but did not associate the practice with soil conservation. Post-harvest grazing commences immediately after maize harvest in June and extends through October. Farmers indicated that pigeon pea crop would curtail

open access post-harvest grazing that led to loss of soil organic matter. This is because farmers are legally bound not to allow their livestock to graze in neighbors' fields that have growing crops. Post-harvest grazing of livestock can distribute about 3.6 kg cow<sup>-1</sup> day<sup>-1</sup> and 0.3 kg goat<sup>-1</sup> day<sup>-1</sup> of excreta (Yona *et al.*, 2020), depending on biomass availability which enriches the soil. However, livestock compact the soil, degrade its structure, and loosen organic rich topsoil exposing it to erosion. Free range grazing also discourages investments in sustainable practices such as agro-forestry, soil and water conservation, and conservation agriculture (Gebremedhin and Swinton, 2003; Teklewold *et al.*, 2020). Farmer knowledge on the importance of pigeon pea in providing year-round soil cover, its root preventing erosion, breaking hardpans and abscised leaves improving soil fertility is not helpful if they lack information on challenges posed by practicing post-harvest grazing.

#### ***4.7.5 Regression of Socio-Demographic Factors Affecting Farmer Knowledge on Sustainable Intensification***

Assessment of farmers who implemented Mbili-Mbili showed that being a part time farmer ( $\beta=0.35$ ;  $p\leq 0.05$ ) and the size of farmer household ( $\beta=0.10$ ;  $p\leq 0.01$ ) were significant positive predictors while years of farming experience ( $\beta=-0.01$ ;  $p\leq 0.05$ ) was a negative predictor of functional knowledge (Table 4.26). Farming experience ( $\beta=0.01$ ;  $p\leq 0.01$ ) was a significant positive predictor while belonging to farmer groups ( $\beta=-0.27$ ;  $p\leq 0.05$ ) was a negative predictor of farmers possessing knowledge on soil fertility management. Being a part time farmer ( $\beta=0.10$ ;  $p\leq 0.05$ ) was a significant positive predictor and, implementing Mbili-Mbili far from homestead ( $\beta=-0.37$ ;  $p\leq 0.01$ ) and area of land under crop cultivation ( $\beta=-0.03$ ;  $p\leq 0.05$ ) were significant negative predictors of farmer knowledge on application of ISFM practices.

Table 4.26. Factors influencing knowledge of farmers implementing Mbili-Mbili technology in Babati

Parameters	Functional		Technical		Soil fertility		Application	
	$\beta$	SE	$\beta$	SE	$\beta$	SE	$\beta$	SE
Age Category: Youth	-0.21	0.22	0.36	0.34	0.17	0.15	0.03	0.08
Sex: Male	0.13	0.16	-0.03	0.24	0.05	0.11	0.06	0.06
Education: Primary and below	-0.07	0.21	0.17	0.32	-0.17	0.14	0.00	0.08
Farming engagement: Part time	0.35*	0.16	-0.28	0.24	-0.07	0.11	0.10*	0.06
Belong group: yes	-0.24	0.18	0.29	0.27	-0.27*	0.12	-0.10	0.07
Distance from homestead: Far	-0.36	0.35	0.74	0.53	0.31	0.24	-0.37**	0.13
Household size	0.10***	0.03	0.04	0.04	-0.01	0.02	0.01	0.01
Farming experience	-0.01*	0.01	0.00	0.01	0.01**	0.00	0.00	0.00
Cultivated farm size	-0.04	0.03	-0.01	0.05	-0.01	0.02	-0.03*	0.01
Information sources	-0.03	0.04	-0.04	0.06	0.03	0.03	-0.02	0.02
Extension interaction	0.07	0.07	-0.02	0.11	0.04	0.05	0.02	0.03
Intercept	4.16***	0.38	2.46	0.58	1.15***	0.26	2.0***	0.14

\*\*\*Significant at 0.01 probability level, \*\*Significant at 0.05 probability level, \*Significant at 0.1 probability level

For farmers implementing doubled-up legume, being a male farmer ( $\beta=-0.47$ ;  $p\leq 0.05$ ), attaining primary education levels ( $\beta=-0.89$ ;  $p\leq 0.05$ ) and having lower years of farming experience ( $\beta=-0.02$ ;  $p\leq 0.05$ ) were significant negative predictors of application knowledge (Table 4.27). Being a youthful farmer ( $\beta=0.49$ ;  $p\leq 0.05$ ), having more years of farming experience ( $\beta=0.02$ ;  $p\leq 0.05$ ) and having an more interactions with agricultural extension staff ( $\beta=0.33$ ;  $p\leq 0.05$ ) were significant positive predictors of farmers having knowledge on soil fertility improvement. Being a male farmer ( $\beta=0.39$ ;  $p\leq 0.05$ ) was a significant positive predictor while being a youth ( $\beta=-0.66$ ;  $p\leq 0.05$ ), the far doubled-up legume was implemented from homestead ( $\beta=-0.47$ ;  $p\leq 0.05$ ), having a larger-sized household ( $\beta=-0.09$ ;  $p\leq 0.05$ ) and having more years of farming experience ( $\beta=-0.02$ ;  $p\leq 0.05$ ) were significant negative predictors of functional knowledge on aspects relating to application of good agricultural practices such as use of certified seeds and conducting proper crop spacing. The model also showed that having a diverse information source ( $\beta=0.35$ ;  $p\leq 0.05$ ) was a significant positive predictor and a larger-sized household ( $\beta=-$

0.13;  $p \leq 0.05$ ) a negative predictor of farmers possessing *functional* knowledge on *optimization* of crop yields under doubled-up legume.

Table 4.27. Factors influencing knowledge dimensions of farmers who implemented doubled-up technology in Babati

Parameters	Application		Soil fertility		Func1		Func2	
	$\beta$	SE	$\beta$	SE	$\beta$	SE	$\beta$	SE
Age Category: Youth	-0.04	0.25	0.49*	0.24	-0.66*	0.26	0.26	0.52
Sex: Male	-0.47*	0.20	0.15	0.19	0.39*	0.21	-0.12	0.42
Education: Primary and below	-0.89*	0.51	0.26	0.48	-0.51	0.53	-0.58	1.05
Farming engagement: part time	0.11	0.21	0.02	0.20	0.33	0.22	0.28	0.43
Belong group: yes	0.21	0.23	0.22	0.22	0.17	0.24	0.29	0.47
Distance from homestead: Far	-0.33	0.36	0.11	0.34	-0.47*	0.37	0.29	0.74
Household size	-0.03	0.03	-0.04	0.03	-0.09*	0.03	-0.13*	0.07
Farming experience	-0.02*	0.01	0.02*	0.01	-0.02*	0.01	0.01	0.02
Cultivated farm size	0.02	0.03	-0.01	0.03	0.00	0.03	-0.02	0.06
Information sources	0.03	0.08	0.00	0.07	0.14	0.08	0.35*	0.16
Extension interaction	0.13	0.18	0.33*	0.17	0.02	0.19	-0.33	0.37
Intercept	5.33***	0.71	3.60***	0.67	5.03***	0.73	3.26*	1.45

*Application* represents application knowledge, *Func1* represents functional knowledge relating to soil, pest and disease management, *Func2* represents functional knowledge relating to crop establishment and yield optimization and soil fertility is soil fertility knowledge. \*\*\*Significant at 0.01 probability level, \*\*Significant at 0.05 probability level, \*Significant at 0.1 probability level.

Gender had a significant influence on farmer knowledge; female participants were highly involved in production of legume crops than their male counterparts. This is because the crop plays important role in meeting their households' food security needs. In addition, use of most legume crops as food for smallholder households largely falls under the domain of female farmers thus increasing their influence in its cultivation (Nakazi *et al.*, 2017). For example, women are reported to provide up to 54% of labor required in production of beans (Venance *et al.*, 2016). Therefore, since doubled-up legume is a pure legume system, involvement of female farmers on its implementation was higher than their male counterparts. However, there could be a takeover by men if the technology is

commercialized considering legumes sales generate more income than maize (Godfrey, 2010; Nakazi *et al.*, 2017).

Increased women involvement in implementing doubled-up legume could have exposed them to more technical aspects of the technology which increased their knowledge over their male counterparts. Unfortunately, exposure of one gender to agronomic knowledge than the other contributes to widening information gap between the two groups. For this reason, MWANGA messaging platform (described in the methodology section) was established by the project to share real-time ISFM related knowledge to diverse farmers in Babati. Waithaka *et al.* (2007) recognized the contribution of female farmers in providing farm labor, which could increase their interactions and enhance their knowledge on introduced technologies. Moreover, similar exposure to agronomic knowledge can be provided to women through increasing their interaction with agricultural extension as it is with men (Venance *et al.*, 2016; McCormack (2018).

Part-time farmers had increased access to different forms of knowledge as they conducted their daily activities. This enables them to try out more capital-intensive innovations or practices than the full-time farmers whose farm investments are paralyzed by their vulnerable incomes. Part-time farmers are therefore exposed to external influences that improve their field management styles (Lien *et al.*, 2006; Šūmane *et al.*, 2018) and helps them access more income (Ikudayisi *et al.*, 2019) to finance capital-intensive innovations (Akinola *et al.*, 2010). Results from this study contradicts Umeh and Olajade (2016) who associated full-time farmers with rapid uptake of research innovations and described part-time farmers as subsistence oriented.

The size of farmer household had a bearing on the level of knowledge of members of the household. Large-sized households have diversity in knowledge and understanding on crop management practices because they have sufficient labor to support labor-intensive agronomic practices (Kansanga *et al.*, 2021) and greater need to meet their food security requirements (Odendo *et al.*, 2010). For this reason, larger households can make strategic and more risky decisions with a potential to solve their food production needs (Macharia

*et al.*, 2014). Contrary, smaller sized households have reduced drive to seek after new forms of agronomic knowledge because of their lower food requirements (Mucheru-Muna *et al.*, 2021).

The influence of farming experience and age of farmers on soil and water conservation knowledge was contradictory. Farmers with more years of farming experience have a long exposure and have witnessed gradual decline in crop yields. This makes them seek more knowledge on soil and water conservation than those with less experience. Experienced farmers are also likely to be more risk averse on adopting other forms of knowledge that may contradict their local knowledge. These farmers are known to “*place their confidence in their old ways and methods*”, Akinola *et al.* (2010)”. On the other hand, youthful farmers lack ISFM application knowledge because they have fewer years of farming experience (Geta *et al.*, 2013). However, they are energetic and can provide labor needed for implementing labor intensive agronomic innovations such as constructing and maintaining soil and water conservation structures. In addition, they have skills to seek knowledge from diverse information sources which elderly farmers might not access. Therefore, efforts to recruit new and youthful farmers to intensify uptake of agronomic innovations might be more fruitful because they are less risk averse and have a longer planning horizon (Kassie *et al.*, 2008). This is unlike the elderly who require a longer unlearning and relearning process to appreciate an emerging innovation (Akinola *et al.*, 2010).

Education levels attained by farmers, the diversity of information they access, and their participation in groups had a great influence on their level of agronomic knowledge. Farmers with post-primary education can easily seek, decipher, and apply more technical knowledge than those with a maximum of primary level of education (Mucheru-Muna *et al.*, 2021). Participation in groups is also an enhancer of farmer interactions and cross-fertilization of agronomic ideas (e.g., Bamire *et al.*, 2002; Akinola *et al.*, 2010; Macharia *et al.*, 2014) which contributes to improving farmer knowledge. In the study area, farmer groups do not engage in practical agricultural training but are used as avenues for accessing farm and social capital (Matere *et al.*, 2022). Existing farmer groups can be mapped and utilized by different agricultural stakeholders as platforms for relaying agricultural

knowledge. This can help to build a mutualistic relationship between access to resources and availability of knowledge to ensure positive impact while conducting farm operations (Bwambale, 2015).

*Hypothesis testing*

**H<sub>0</sub>:** Different socio-economic factors such as gender, age and household income do not influence farmer knowledge on implementing improved cropping systems.

Results of this study indicate that under similar conditions as those of the study area, different socio-economic factors such as age, sex, size of household, education, distance from residence among others influence farmers' technical, functional, application and soil fertility knowledge associated to introduced cropping systems. This resulted to rejection of the null hypothesis.

## CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

This study informs on the need for developing new cropping systems that can solve the problem of low legume yields under cereal-based systems without compromising on the yields of maize. Mbili-Mbili is an innovative cropping system that had an average of US\$ 150 net revenue more than other treatments and was the most stable treatment across a period of four seasons. The system was more climate resilient because it accommodates three crop species compared to two in other improved cereal-legume and legume-legume treatments. Beyond spatial configurations, stripping and de-topping upto 2 t ha<sup>-1</sup> of maize biomass per acre resulted in 15.4% increase in pigeon pea grain yield under maize intercropping. However, topping beyond 2 t ha<sup>-1</sup> of biomass would result in a diminishing return on pigeon pea yield. If guided by accurate seasonal weather forecasting, doubled-up legume rotation is an economically feasible system with maize equivalent yields of upto 12.5 t ha<sup>-1</sup> during a good season.

Deficiencies in soil N, P and C is a dominant challenge that affects smallholder farming systems of Babati. It is requisite that farmers are sensitized on combined application of inorganic and organic fertilizers to address existing macro and micronutrient deficiencies. Innovative cropping systems such as doubled-up legume with high potential for fixing biologically available N can be introduced for adoption by smallholder farmers. Doubled-up legume can fix upto 130 kg N ha<sup>-1</sup> while leaf abscission of upto 2 t ha<sup>-1</sup> can generate a rich organic matter to promote soil health. This can help to reduce degradation of soils in Babati, where fertilizer utilization by farmers is still low.

Ensuring farmer-centered participatory testing of agronomic innovations was an essential tool assessing the performance of introduced technologies before making adoption related decisions. Farmer assessment of technologies under study, over the different seasons, showed high preference for Mbili-Mbili against other treatments. This was linked to the high yields attained and crop diversification that allowed production of different crop species in small land holdings. However, the intensive labor required for its implementation (especially at planting) was indicated as the major dis-incentive for its

adoption by farmers. However, farmers appreciated that the technology reduced weeding labor requirements by half compared to conventional maize-pigeon pea system because the thick canopy generated helped to smother weeds. In addition, it was established that male-heads were the dominant decision makers on majority of farm operations. They had absolute power over control of agricultural land, produce sales and derived proceeds. This made female spouses significant providers farm labor, but only controllers of crops cultivated for subsistent purposes. This may limit scaling of technologies preferred by female farmers if crops highly valued by their male spouses are not integrated. Female farmers can also refrain from taking up technologies that are income oriented but associated with high labor requirements.

Technical themes of innovations such as Mbili-Mbili and agronomic practices like fertilizer application, manure management, and soil and water conservation are knowledge intensive, a condition that may slow down their implementation by farmers. More practical training sessions and encouragement of farmers to participate in knowledge generation platforms is paramount. Farmers can be encouraged to join groups aimed at generation of agricultural knowledge such as farmer research teams, farmer field schools, and farmer research networks. The agricultural extension staff and other stakeholders involved in farmer empowerment can ride on such platforms to impact farmers with the necessary agronomic knowledge. Functional and application related knowledge themes can be separated from more technical themes to ensure farmers are able to decipher and apply the knowledge in their farm operations. Technology development and knowledge dissemination should also be conducted in such a way that they meet the needs of both the young and elderly people. This is because the level of understanding and the ease of adoption and scaling by the two groups is influenced by their differences in risk averseness, conservativeness to new and/or contradicting knowledge and scope of their production plans.

## **5.2 Recommendations**

1. Mbili-Mbili can increase the climate resilience of smallholder farmers through crop diversification and improving yields of the intercrop companions. However, agricultural mechanization is essential to reduce planting labour, which farmers indicated as the major adoption challenge for Mbili-Mbili.
2. A rotational system involving sole maize and doubled-up legume was identified as a profitable agricultural venture, but highly vulnerable to changes in seasonal weather conditions. Governments and stakeholders can help to make smallholder farming more successful by providing climate information service to help in targeting such cropping systems to specific seasons to optimize attained benefits.
3. Deficiencies of N, P and specific micronutrients like Zn are dominant across farmer fields in the study area. This contributes to the existing yield gap which is compounded by low fertilizer adoption rates. Farmer sensitization on importance of fertilizer and organic resource application to unlock yield gap is needed. In addition, the existing bracket fertilizer recommendations require replacement with site-specific recommendations to increase both nutrient and agronomic use efficiencies of cropping systems and individual fields. Site-specific fertilizer recommendations can also be guided by seasonal weather predictions to avoid nutrient loss to the immediate environment.

## **5.3 Contribution to knowledge**

This study demonstrates the potential of innovative cropping systems, such as Mbili-Mbili and doubled-up legume, to enhance legume yields and climate resilience, offering valuable insights for agricultural research on sustainable intercropping practices. It enlightens students in academia on the benefits and importance of crop diversification and soil health improvements. Besides, it guides agricultural extension on structure of farmer knowledge, ability to decipher different crop production themes and need for participatory approaches and farmer-centered innovations for improved technology adoption. In addition, it provides a basis for policy recommendations focused on addressing labor dynamics, gender inclusion, and sustainable nutrient management in smallholder farming systems.

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## APPENDICES

### Appendix 1. Matrix for Relative Ranking of Innovation by Farmers in Babati, Tanzania

Treatment Id	Treatments	Rank	Reason
1.	Sole maize (Syngenta)		
2.	Maize (Syngenta) pigeon pea intercropping- No topping		
3.	Maize (Syngenta) pigeon pea intercropping- Maize topped		
4.	Doubled- up legumes		
5.	Maize (2 seeds per hole) pigeon pea intercropping		
6.	MBILI- MBILI		
7.	Maize (Meru) pigeon pea intercropping		

**Appendix 2. Matrix for Relative Rating of Innovation by Farmers in Babati,  
Tanzania**

SI indicator	Sole maize	Maize - pigeon peas (No topping)	Maize - pigeon pea Maize topped	Doubled -up legumes	Maize (2 seeds) pigeon pea	MBILI-MBILI	Maize (Meru) pigeon pea	Rate
Yield								
Profitability								
Labor demand								
Food security								
<b>Total</b>								
<b>Average</b>								
<b>Final Rate</b>								
Rating scores	100% = Very good 75% = Good 50% = Average 25% = Poor							

### **Appendix 3. Household Survey Tool for Gender Perception Assessment Following Introduction of New Innovative Technologies in Babati, Tanzania**

#### **Section A**

##### **Baseline household information**

*(Remind the interviewee that they are free to choose to answer or not to answer any question they consider sensitive and can also withdraw anytime from the discussions).*

Name of person collecting data:

Name of the respondent farmer:

1. What is the age of the respondent?
2. What is the position of respondent within the household?
3. What is the gender of the household head?
4. What is the age of the household head?
5. What is the highest level of education of the household head?
6. What is the occupation of the household head?
7. Number of males (older than 18 yrs.) in household.
8. Number of females (older than 18 yrs.) in household.
9. Number of children (<18 yrs.) in household.
10. Name of village.
11. What is the total area of land farmed by this household?
12. What type of land ownership does your household possess?
13. How many years have you been involved in crop farming?
- 14.** Was your household selected and trained on testing the new technologies under baby trials? *(If 'Yes', go to question 15, if 'No' go to Section G)*
15. Did you establish a baby trial for testing the new technology on your farm? *(If 'Yes', go to question 16, if 'No' go to Section F)*
16. What type of technology did your household test?
17. Did you plant beans on baby trial in the last season?
18. How many phases of beans did you plant in the last season?
19. If one, what prevented you from sneaking a second bean phase in your baby trial last season?

20. If none, why did you decide not to plant beans in your baby trial?
21. Did you plant pigeon peas (Mbaazi) on baby trial in the last season?
22. If No, why did you decide not to plant pigeon peas in your baby trial?
23. Specify number the of seasons you have been involved in testing of the new technology?

## **Section B**

### **Decision making and resource control**

24. Who in the household owns the land that was allocated for technology testing?
25. How can you categorize the fertility level of the field allocated for technology testing?
26. What is the approximate distance (in km) of the trial plot from homestead?
27. Did you modify the design of the trial relative to the procedure provided during training?
28. If yes, what were the modifications done? (*options to be limited after pretesting the tool*)
29. Who in household made the decision on re-designing the trial?
30. Why did you modify the trial set-up?
31. What area of land was allocated to technology testing during the 2019 season?
32. What area of land was allocated to technology testing during the 2020 season?
33. If there is change in area, why did you decide to change the area under the new innovation?
34. Did you top dress maize in the trial? (*for only farmers conducting Mbili-Mbili technology*)
35. Did you top dress maize under your conventional practice?
36. Who made the decision on time and method of top dressing?
37. What made you not to top dress maize in your conventional practice?

## **Section C**

### **Division of labor by gender**

38. What method was used in land preparation?
39. Who made decision on the method used for land preparation?
40. Comparing labor demands for planting both conventional system and the new technology, which of the two is more labor intensive?
41. How much time was taken to plant an acre of land under normal practice?
42. How much time was taken to plant the area under baby trial?
43. What could have caused the differences in time and labor demands between the two systems?
44. Who provided labor for planting the baby trial?
45. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
46. Who made the decision on labor source for planting the baby trial?
47. Was weeding conducted on the trial?
48. How many times was the trial weeded?
49. Who provided labor for weeding?
50. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
51. Who decided when to weed the trial?
52. Who decided on labor source for weeding?
53. How long did it take to weed the trial?
54. How long did it take to weed equal area under conventional practice?
55. What do you think caused the differences in time taken to weed the two systems?
56. Did you identify any crop pest or disease attack in the trial?
57. How do you compare the infestation of pest in the trial versus the conventional practice?
58. If variability exist, what could have caused the differences in intensity of pest and disease infestation between the two systems?

59. Did you carry out any pest and disease control measure?
60. If no, why didn't you conduct crop pest and disease management?
61. If you observed differences in labor demands for pest and disease management in the two systems, what could have caused the differences?
62. Who provided labor for pest and disease control?
63. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
64. Who made the decision on time and type of pest and disease control measures to apply?
65. Who made the decision on labor source for pest and disease control?
66. Did you harvest beans in the trial last season?
67. If no, why didn't you harvest beans after planting them in the trial?
68. If yes, how many phases of beans did you harvest?
69. Who provided labor for bean harvesting?
70. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
71. How long did it take to harvest beans in the trial plot?
72. Who made the decision on time to harvest beans?
73. Who made the decision on labor source for harvesting beans?
74. Who provided labor for post-harvesting processing operations for beans?
75. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
76. Did you harvest maize in the trial in last season?
77. If no, what caused the failure for maize harvesting?
78. If yes, who provided labor for harvesting maize?
79. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
80. How long did it take to harvest maize in the trial?
81. Who made the decision on time to harvest maize?
82. Who made the decision on labor source for harvesting maize?

83. Who provides labor for post-harvesting processing operations for maize?
84. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
85. Did you harvest pigeon peas in the trial?
86. If no, what caused the failure for harvesting the pigeon peas in your baby trial?
87. If yes, who provided labor for harvesting pigeon peas?
88. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
89. How long did it take to harvest pigeon peas in the trial?
90. Who made the decision on time to harvest pigeon peas?
91. Who made the decision on labor source for Harvesting pigeon peas?
92. Who provides labor for post-harvest processing of pigeon peas?
93. If more than one gender/casual labor involved, what was the proportion of involvement for each member?
94. Did introduction of the new technology result in increased labor burden for the household?
95. Which aspect of the new technology led to increased labor burden?
96. Estimate the proportion of labor that was increased by the new technology?
97. Overall, which member of your household was affected by increased labor requirement of the new technology?

## **Section D**

### **Yield assessment**

*(Remind the interviewee that they are free to choose to answer or not to answer any question they consider sensitive and can also withdraw anytime from the discussions).*

98. What was the average maize yield harvested from the new technology in the last season?
99. What was the average maize yield harvested from one acre under conventional practice during last season?

100. Did your household sell the maize harvested in the last season?
101. Where/to whom did you sell the harvested maize?
102. How many months after harvesting did you take before commencing on maize sale?
103. What was the quantity of maize sold?
104. During the period when you sold your maize, what was the price of one bag of maize?
105. Who in the household makes the decision on spending income generated from maize sale?
106. What was the average beans yield harvested from the new technology in last season?
107. What was the average bean yield from an acre of conventional practice last season?
108. Did your household sell the beans harvested in the last season?
109. Where/to whom did you sell the harvested beans?
110. How many months after harvesting did you take before commencing on bean sale?
111. What was the quantity of bean sold?
112. During the period when you sold your beans, what was the price of a bag of beans?
113. Who in the household makes the decision on spending income generated from bean sale?
114. What is the average yield of pigeon peas harvested from the trial in last season?
115. What is the average yield of pigeon pea from one acre of land under conventional practice harvested this season?
116. Did your household sell pigeon pea grains that were harvested in the last season?
117. Where/to whom did you sell the harvested pigeon pea?
118. How many months after harvesting did it take before commencing pigeon pea sale?
119. What was the quantity of pigeon pea sold?
120. During the period when you sold your pigeon pea, what was the price of a bag of pigeon pea?
121. Who in the household makes the decision on spending the income generated from pigeon pea sale?

122. What were the important observations you identified while testing the new technology?
123. Considering your overall evaluation of the new technology, would you be willing to scale up the innovation in your farm?
124. Considering the labor and time invested, what area of land would you allocate if you were to scale up this technology?
125. What makes you opt to allocate it that size of land?
126. Would you be willing to scale out the innovation by training other farmers?
127. Have you already trained other farmers on implementing the new technology?
128. How many farmers have you trained so far?
129. Of the farmers, whom you trained, how many implemented the innovation?
130. If no, what made you decide not to scale up the new technology?

## **Sec E**

### **Role of farmer knowledge, groups, institutions, and markets in technology adoption**

131. Has any household member participated in any crop production training?
132. Who in the household has participated in crop production training?
133. Have you received any training on post-harvest handling of your crop produce?
134. What type of post-harvest handling technique did you learn?
135. Who in the household received the post-harvest handling training?
136. Are you already implementing any post-harvest management technique?
137. Which post-harvest management technique are you currently practicing?
138. Who in the household conducts the post-harvest management technique on your produce?
139. What is the average time spent in conducting post-harvest management on your crop produce in an average season?
140. How can you describe the market prices for the different crop components under the new technology?
141. Apart from this project, are there organizations, institutions or persons helping you in experimentation and scaling of new technologies?

142. Who are these organizations, institutions, or persons?
143. Are you a member of an organized farmer group that is involved in technology experimentation and adoption?
144. How does the farmer group(s) support you in technology experimentation and adoption?

## **Sec F**

### **Resource flows**

145. What benefits, besides income, do you get from pigeon pea cultivation?
146. Do your household utilize pigeon pea grain as food?
147. If no, why are pigeon peas not utilized as food for your household?
148. Do you utilize pigeon stalks as fuel?
149. How many months does fuel generated from one acre of pigeon pea cover your household?
150. How is labor saved after utilizing pigeon pea as fuel used by women?
151. Where do you take the pigeon pea husks after threshing of pods?
152. If sold, what proportion of pigeon pea husks do you sell?
153. Did practicing the new technology help in diet diversification for your household?
154. If yes, how did the new technology help in diet diversification for your household?
155. If no, why do you think practicing the new technology had no impact on your household's diet diversification?
156. Did practicing the new technology help in increasing the food secure months in your household?
157. If yes, how was the food security status of your household improved?
158. If no, why do you think practicing the new technology had no impact on the food security status for your household?
159. Did you experience fluctuation in pigeon pea prices during the previous seasons?
160. What were your experiences regarding the pigeon pea market?
161. Did you change area allocated to pigeon peas after price fluctuation of the crop?

162. How did your land allocation to pigeon pea change after price fluctuations?
163. How do you handle maize residues after harvest? (*Capture residue exchanges i.e., manure/labor in the choices*)
164. How do you handle bean residues after harvest? (*Capture residue exchanges i.e., manure/labor in the choices*)
165. How do you handle pigeon pea residues after harvest? (*Capture residue exchanges i.e., manure/labor in the choices*)
166. Do you allow livestock to freely graze in your crop fields after crop harvest?
167. How often do animals freely graze in your crop fields after harvest?
168. Why do you allow livestock to directly graze in your crop fields?

## **Section F**

### **For farmers who did not establish the baby trials**

169. Why did you decide not to conduct the trials?
170. How did you use the different inputs you were provided for establishing the trial?
171. Did you visit any farmer field where your technology of choice was tested?
172. What are your views regarding the performance of the technology?
173. Given another opportunity, would you like to participate in similar technology testing?
174. Assuming technology testing is not repeated, would you adopt or scale it?
175. If yes, why would you adopt/scale the new technology?
176. If no, why wouldn't you adopt/scale the new technology?

## **Section G**

### ***For the control farmer group***

177. Did you plant certified maize seeds in your fields during the last season?
178. What method did you use for crop spacing? (*behind tractors, animal ploughs or gardener's line*)

179. What was your main crop nutrient sources for your fields? (*Inorganic fertilizers, manure, no inputs applied, others (specify)*)
180. Did you encounter crop and disease attack in your fields?
181. What was the extent of pest and disease attack? (*Likert scale provided*)
182. Did you plant beans in your fields during the last season?
183. How many phases of beans did you plant in your field?
184. Besides maize, what crops did you intercrop with beans during the last season?
185. What was the average quantity of beans harvested from one acre of your fields?
186. What was the average quantity of maize harvested from one acre of your fields?
187. What was the average quantity of pigeon pea harvested from one acre?
188. Have you ever attended any post-harvest handling training?
189. What was the post-harvest management option conducted on your produce?
190. Do you allow free grazing of livestock after completing crop harvesting?
191. Do you belong to any common interest farmer group?
192. If yes, what is the overall aim of your farmer group?
193. Did you receive agronomic advisory in the last season?
194. How important is the agronomic advisory services during your agricultural operations? (*Likert scale*)
195. To what extent are you applying soil and water management strategies in your field? (*Likert scale*)

*Thank you for your time and participation in this survey!!*

## **Appendix 4. Focus Group Discussion Tool for Farmers' Perception Assessment Following Introduction of Two Cropping System Innovations in Babati, Tanzania**

### **Gender assessment FGD tool**

#### **Baseline farmer group information**

Name of moderator facilitating the farmer discussion:

Name of the note taker during the farmer discussion:

Name of technology the farmers tested:

Number of farmers in the group discussion:

Number of males (older than 18 yrs) in the discussion:

Number of females (older than 18 yrs) in the discussion:

Name of village:

#### **Section A**

##### **Division of labor by gender**

*(Remind the participants that they are free to choose to answer or not to answer any question they consider sensitive and can also withdraw anytime from the discussions).*

1. How did introduction of the new technology affect labor demands within your households?
2. Which aspect of the new technology led to increased labor burden?
3. Estimate the proportion of labor that was increased by the new technology? *(compared to conventional practice)*
4. Overall, which member of your households was affected by increased labor requirement after introduction of the new technology?

#### **Sec B**

##### **Role of farmer knowledge, groups, institutions, and markets in technology adoption**

5. What kind of crop production trainings have members of your households participated? *(Probe whether the trainings were attended by male or female household members)*
6. Which other new agronomic technologies have you ever tested?
7. What were your experiences after testing the *(above mentioned)* technologies?
8. What type of post-harvest handling techniques have you ever been trained? *(Probe whether training attended by male or female household members)*

9. Which post-harvest management technique are you currently implementing? (*Probe who mainly conducts the activity, male or female household members*)
10. What is the average time spent in conducting post-harvest management on your crop produce in an average season? (*For both categories of farmers i.e., trained and not trained*)
11. How can you describe the market for the different crop species planted in the new technology under test?
12. Apart from this project, which other organizations, institutions or persons are helping you in experimentation and scaling of new technologies?
13. How do the locally organized farmer groups support you in technology experimentation and adoption?

## **Section D**

### **Resource flows in farmer field**

14. What benefits, besides income, do you get from pigeon pea cultivation?
15. What are your opinions on utilization of pigeon pea as food for your households? (*probe whether they consume pigeon peas or its entirely sold, why they don't consume it*)
16. How many months does pigeon pea fuelwood from an acre of land cover your household?
17. How is labor saved after utilization of pigeon pea as fuel, used by women?
18. Where do you take the pigeon pea husks after threshing your pods? (*If sold probe proportions sold, for how much and source of the market*)
19. How did the new technology help in diet diversification for your household? (*probe on household food diversity, opinion on improved nutrition*)
20. How was the food security status of your household improved after implementing the technology? (*Probe on increase in months of food safety, sale of produce to buy other supplementary food*)
21. What were your experiences regarding the pigeon pea market during the previous seasons? (*Probe for price fluctuations and how this affected farmers' production behavior*)
22. How did land allocation to pigeon pea change following prevailing market of pigeon pea?
23. What are the major lessons that you learnt after testing the new technology?

24. Where do you take maize residues after harvest? (*Probe on residue exchanges i.e., manure/labor in the choices*)
25. Where do you take bean residues after harvest? (*Probe on residue exchanges i.e., manure/labor in the choices*)
26. Where do you take pigeon pea residues after harvest? (*Probe on residue exchanges i.e., manure/labor in the choices*)
27. What is your opinion on allowing livestock to directly graze in your crop fields? (*Probe how often this happens, whether household or community grazing and type of livestock*)
28. Overall, what is your opinion on the performance of new technology relative to conventional practices? (*Probe on crop vigor, pest and disease attack, yields and household income*)

*Thank you for your time and participation in this discussion!!*

**Appendix 5. Assessment of Knowledge Level of Farmers Conducting Mbili-Mbili Technology in Babati, Tanzania**

Farmer Name:

Age:

Marital Status:

Status in the household:

Education level:

<i>Indicators</i>	<i>Have you received training on/by:</i> 1) <i>Yes</i> 2) <i>No</i>	<i>How effective was the training on/by:</i> <i>Score: 1 represents very poor and 5 represents excellent</i>	<i>How do you rate the value of training on/by:</i> <i>Score: 1 represents very poor and 5 represents excellent</i>	<i>How do rate your knowledge on/by:</i> <i>Score: 1 represents very poor and 5 represents excellent</i>	<i>Indicate extent of using:</i> <i>Score: 1= very low and 5= very high</i>
Implementation of the new technology					
Proper crop spacing					
Using certified seeds					
Timely planting					
Fertilizer use					
Manure use					
Pest and disease control					
Soil and water conservation					
Agricultural advisory service					

**Kindly indicate your level of agreement with the following statements on farm management practices conducted during the implementation of doubled-up legume technology. Scores: 1= Strongly disagree, 2= Disagree, 3 = not sure, 4= Agree, 5= Strongly agree**

	<i>Indicator statement averse</i>	1	2	3	4	5
1.	For increased crop yields, it is important to use certified seeds from recognized dealers.					
2.	Planting is best done after rainfall on-set to allow crops to maximally utilize soil moisture.					
3.	Using gardener's line achieves high plant population than planting behind ploughs.					
4.	Mbili-Mbili technology involves planting three crop species i.e., maize and two legumes.					
5.	In Mbili-Mbili technology, beans are planted adjacent the double maize rows.					
6.	Two bean phases can be planted in a year within a Mbili-Mbili intercropping system.					
7.	Productivity of Mbili-Mbili is not affected by plant species' competition for nutrients and light.					
8.	Mbili-Mbili allows same maize rows as properly spaced conventional intercropping system.					
9.	Mbili-Mbili increases light penetration and legume yield than conventional intercropping.					
10.	Mbili-Mbili system is more risk averse than practicing conventional intercropping.					
11.	Basal fertilizer is required at sowing even if maize is to be top-dressed at later growth stages.					
12.	You can apply top-dressing fertilizer on maize even if you did not apply fertilizer at planting.					
13.	Fertilizers and manure can be applied at the same land during crop production.					
14.	Fallen pigeon pea leaves helps to improve soil fertility especially if manure is limited.					
15.	Cultivating pigeon pea helps to break hard pans associated with continuous land cultivation.					
16.	Year-round soil cover provided by pigeon pea conserves soil water and prevents erosion.					
17.	Pigeon pea roots are important for protecting soil from being eroded by surface run-off.					
18.	Crop rotation in fields affected by diseases and pests helps to break cycles of re-occurrence.					
19.	Pest and diseases should be controlled immediately their signs are observed to evade losses.					
20.	Mbili-Mbili provides more months of food security than conventional intercropping.					

**Appendix 6. Assessment of Knowledge Level of Farmers Conducting Doubled-up Legume Technology in Babati, Tanzania**

Farmer Name:

Age:

Marital Status:

Status in the household:

Education level:

<i>Indicators</i>	<i>Have you received training on/by: Yes No</i>	<i>How effective was the training on/by: Score: 1 represents very poor and 5 represents excellent</i>	<i>How do you rate the value of training on/by: Score: 1 represents very poor and 5 represents excellent</i>	<i>How do rate your knowledge on/by: Score: 1 represents very poor and 5 represents excellent</i>	<i>Indicate the extent of using: Score: 1= very low and 5= very high</i>
Implementation of the new technology					
Proper crop spacing					
Using certified seeds					
Timely planting					
Fertilizer use					
Manure use					
Pest and disease control					
Soil and water conservation					
Agricultural advisory service					

**Kindly indicate your level of agreement with the following statements on farm management practices conducted during the implementation of doubled-up legume technology. Scores: 1= Strongly disagree, 2= Disagree, 3 = not sure, 4= Agree, 5= Strongly agree**

	<i>Indicator statement</i>	1	2	3	4	5
1.	For increased crop yields, use certified legume seeds from recognized dealers.					
2.	Using gardener's line achieves higher plant population than sowing behind the plough					
3.	Doubled-up legume system involves planting only two legume species on same land.					
4.	Beans and pigeon pea in doubled-up legume can be planted on different days.					
5.	Planting is done upon rainfall on-set to allow crops to maximally utilize soil moisture.					
6.	Both pure bean and doubled-up legume systems allow for planting two bean phases.					
7.	Pigeon pea does not create shade on beans because they grow slowly and mature late.					
8.	Doubled-up legume system improves soil fertility more than the pure bean system.					
9.	Fallen pigeon pea leaves helps to improve soil fertility especially if manure is limited.					
10.	Fertilizers and manure can be applied together during crop production.					
11.	Rotating doubled-up legumes with maize enhances utilization of deposited nutrients					
12.	Cultivating pigeon pea helps to break hard pans caused by continuous land cultivation					
13.	The year-round soil cover provided by pigeon pea prevents soil erosion.					
14.	Pigeon pea-bean systems protect soil erosion compared to pure bean systems.					
15.	Allowing livestock to graze in crop fields destroys soil structure and fertility.					
16.	Doubled-up legume prevents field invasion by livestock compared to pure beans systems.					
17.	Crop rotation in fields affected by diseases and pests helps to break their cycles.					
18.	Pest and diseases should be controlled immediately signs of crop attack are observed.					
19.	Doubled-up legume provides more months of food and income than pure bean system.					
20.	Doubled-up legume cushions farmers from total crop loss during seasons of drought.					



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Our Ref: N85/20129/20

Date: 7<sup>th</sup> October, 2021

The Director General,  
National Commission for Science, Technology & Innovation,  
P.O. Box 30623-00100,  
**NAIROBI**

Dear Sir/Madam,

**RE: RESEARCH AUTHORIZATION FOR MR KINYUA M. WANJOHI- REG. NO. N85/20129/20**

I write to introduce Mr. Wanjohi who is a Postgraduate Student of this University. He is registered for a Ph.D. degree programme in the Department of Environmental Science & Education in the school of Environmental Studies.

Mr. Wanjohi intends to conduct research for Ph.D. thesis entitled, "Agro-Economic of Maize-Based Cropping Systems and Gender Perspectives in Babati, Tanzania".

Any assistance given will be highly appreciated.

Yours faithfully,

**PROF. EMSHIBA KIMANI**  
**DEAN, GRADUATE SCHOOL**

EM/cao



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