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Agronomic and economic performance of legume-legume and cereal-legume intercropping systems in Northern Tanzania

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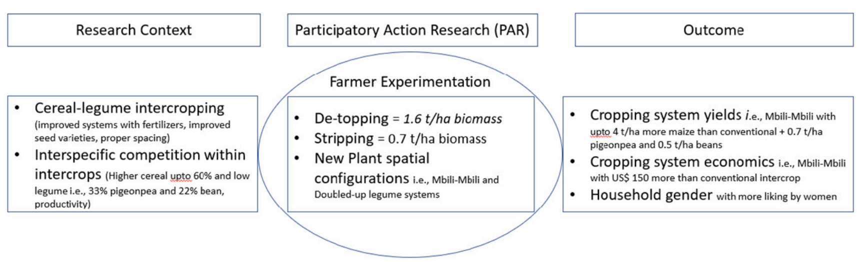
HIGHLIGHTS

- Crop spatial configurations differ on effects they pose on productivity and overall economics of cereal-legume intercrops'.
- Achieving high legume productivity and economic benefits, is hampered by competition among intercropping components.
- Doubled-up legume (involving beans)-Sole maize rotation is a risky system that may not be an immediate choice for farmers.
- Mbili-Mbili provides at least $150 higher revenues that are more stable across seasons than other cereal-legume systems.
- Mbili-Mbili is recommended for household diet diversification of vegetables, pulses, and cereals with reducing landholding.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Cereal-legume intercropping, a common practice among farmers in sub-Saharan Africa (SSA), is important for crop diversification, soil fertility improvement, household nutrition and climate adaptation. However, cereals often outcompete the intercropped legumes for growth resources resulting in low legume yields.

OBJECTIVE: The objectives of this study were: i) assessing the effects of different intercropping options (crop spatial configurations) and maize crop (*Zea mays L.*) management innovations on productivity and economic benefits to farmers and ii) examining how farmers adapt new intercropping technologies to meet their household food security needs.

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METHODS: The study was undertaken in six on-farm researcher-designed and managed trials in high and low rainfall agro-ecological zones of Babati District in Tanzania, during four cropping seasons (2018–2021). The cropping systems tested included a sole maize system rotated with a legume-legume intercrop (Doubled-up legume), an innovation involving two maize rows intercropped with two legume species (Mbili-Mbili), maize-legume intercrop both with and without de-topping, maize-legume intercrop (2 maize plants at 50 cm intra-space, de-topped), maize-legume system (maize with vertical leaf architecture) and a farmer practice. The Mbili-Mbili technology adaptation assessment was conducted on 225 farmers during the 2021 cropping season.
RESULTS AND CONCLUSIONS: Overall, maize grain yields increased by up to 56% in improved compared to farmer intercropping practices ($P \leq 0.05$). There were no significant differences in maize grain yield among the improved practices. Significantly higher pigeonpea (*Cajanus cajan*) yields of between 71% and 113% in 2020 and between 65% and 140% in 2021 were observed under Doubled-up legume and between 63% and 124% under local farmer practices in 2020 than in the improved cereal-legume practices. Across the study period, net revenues of sole maize and Doubled-up legume rotations were both the highest and lowest relative to other intercropping options, depending on the starting phase (US$ 653 sole maize and US$ 326 legume phase starting). These were also associated with the highest variances indicating instability. Mbili-Mbili intercropping system had not only high net revenue i.e., a mean of US$623 per hectare, but also more stable. Farmers perceived that Mbili-Mbili increased food security and 96% were willing to implement the system without project support.
SIGNIFICANCE: Mbili-Mbili is recommended for adoption by farmers because of its potential economic benefits, food security and resilience in the current unpredictable weather and climate patterns.

1. Introduction

Cereal and legume intercropping systems have the potential to improve soil fertility and food security of smallholder farmer households in sub-Saharan Africa (SSA). These systems have higher land equivalent ratios (LER) than sole crops of either continuous cereals or cereal-legume rotations (Tang et al., 2021; Li et al., 2020). However, achieving high legume productivity and the associated economic benefits under intercropping systems, is often hampered by competition for light, water, and nutrients, among the component crops (Lithourgidis et al., 2011; Kimaro et al., 2009). Strategies for minimizing such competitions include choice of appropriate crop species and/or varieties (Myaka et al., 2006), specific crop management including planting patterns (Woomer et al., 2004; Rajkumara et al., 2020) and increasing level of fertilization to support increased nutrient demands. In Northern Tanzania and elsewhere in East and Southern Africa, growing long duration (about 10 months) pigeonpea varieties in maize-pigeonpea intercropping results in the same yield for maize as observed under maize sole crops, i.e., pigeonpea does not compete for resources with maize because they have different growth patterns (Myaka et al., 2006). On the other hand, a 33% reduction in pigeonpea yield and 22% in beans (*Phaseolus vulgaris*) has been reported under maize intercrops (Kimaro et al., 2009; Venance et al., 2016; Laizer et al., 2019). Improving the productivity of these legumes while still maintaining the same level of maize productivity as the sole crop systems is desired.

Legume integration within cereal cropping systems is a climate smart option for cushioning farmers against crop failure under the increasingly variable climate (Madembo et al., 2020). Thus, introducing multiple intercropping options could expand the basket of cropping systems configurations for farmers to increase household food security and economic gains. New plant configurations have been developed to manage legume productivity within intercrops. Strip cropping of cereals and legumes involving two rows of maize planted at close distances (spacing of 50 cm) leaving a large space for legumes before the next two rows of the cereal has been shown to increase productivity of the legume while preserving that of the cereal component (Woomer et al., 2004). This crop configuration called MBILI (Managing Beneficial Interactions for Legume Intercrops) has been recommended for increasing legume productivity in East Africa (Ogutu et al., 2012). The productivity of MBILI is attributed to its potential to allow penetration of photosynthetically active radiation (PAR) to the understorey legumes (Mucheru-Muna et al., 2010). Studies have reported comparatively similar maize production (Ng'etich et al., 2014) and an increment of 250 kg ha^{-1} on bean yields under MBILI (Thuita et al., 2011) making it more economically viable than the farmer intercropping practices. A different configuration involving only legumes in what is called Doubled-up legume (DUL) of pigeonpea and groundnuts/soybean tested by Africa RISING in Malawi has higher economic benefits, improved food diversity and protein nutrition of households and increases soil fertility relative to legume sole crops and cereal-legume intercrops (Phiri et al., 2012; Smith et al., 2016; Chitsike et al., 2017; Chikowo et al., 2020; Njira et al., 2021). Other agronomic practices reducing cereal competitions with legumes, such as the long duration pigeonpea, include de-topping of maize at physiological maturity, i.e., nipping or removal of terminal portion of the plant (Rajkumara et al., 2020), and stripping (removal) of some lower leaves. A recent review shows variations in de-topping to include timings e.g., at 30 days after silking, or after physiological maturity, removing everything above the 10th internode, or stripping to remove the top 6 leaves or all the leaves above the cob (Rajkumara et al., 2020) has slight or no reduction in maize grain yield (Rajkumara et al., 2020; Mashingaidze and Katsaruware, 2010). The integration of variable crop configurations with practices such as de-topping and stripping could result in even more legume yields but no studies have been observed taking such an integrated approach.

Maize varieties differ in their leaf architecture, a feature used to manage light penetration (Girardin, 1992; O'leary and Smith, 2004) and reduce extent of competition between the maize and legume intercrops (Davis and Woolley, 1993; Kanton and Dennett, 2008). O'leary and Smith (1999, 2004) identified monocultures-focused breeding of varieties without attention to intercrop adaptability as a major weakness since intercropping is a common practice among farmers in SSA. O'leary and Smith (2004) introduced maize variety selection based on system yields where all crop components are considered, unlike selection based on maize yields only as is the case for sole crop systems. As early as 1980s, increased legume yields under maize with erect upper leaves have been observed and attributed to more light penetration (Wahua et al., 1981), although not much work is undertaken on this topic lately. New maize varieties such as Meru 513 with erect canopy are available for farmers but data of their effect on legume yields when grown under intercropping systems are scanty (Kanton and Dennett, 2008).

This study evaluated various intercropping and maize crop management innovations for increasing system benefits especially through increasing legume productivity (pigeonpea and beans) within the commonly practiced maize-pigeonpea systems in Northern Tanzania. The specific objectives were to: i) assess the effects of different crop spatial configurations and maize crop management innovations on productivity and overall system economics within high and low rainfall midlands of Babati, Tanzania and ii) examine how farmers adapt new technologies to meet their household food security needs.

2. Methods

This study was undertaken in Babati District, in Northern Tanzania located between latitudes 3° and 4° South and longitudes 35° and 36° East. Two experimental trial sites were set in each of Riroda and Sabilo villages located in the high rainfall midlands agroecological zone which lies between 1500 and 1950 m.a.s.l. and receives unimodal rainfall ranging between 900 and 1100 mm per year. Two additional sites were laid out in Gallapo village located in low rainfall midlands located between 1200 and 1500 m.a.s.l and receiving between 750 and 900 mm of annual rainfall. During this study, daily rainfall was recorded from 2019 to 2021 using automatic weather stations *(WatchDog 2000 Series by Spectrum Technologies Inc.)* located in two of the three experimental sites. Being on the same agroecological zone, rainfall pattern in Riroda usually resemble that of Sabilo. Soils are mostly Ferralsols with limitations of N and P (Adu-Gyamfi et al., 2007) and micronutrients such as Zn and Mn in specific places. Landholdings range between 1 and 2 ha in the high rainfall midlands and 3–10 ha in the low rainfall midlands (own data). Average productivity under farmer practices is 2.8 t ha^{-1} for maize, 0.7 t ha^{-1} for pigeonpea (Mugi-Ngenga et al., 2021) and 0.24 t ha^{-1} for common beans (Laizer et al., 2019). The farmer practices commonly involve growing legumes (pigeonpea and common beans) as intercrops with maize.

2.1. Trial design and treatments

The experiments were conducted between 2018 and 2021 (with six on-farm trials per season) and set as randomized (per block and field) complete block design with 7 treatments. The experiments were designed to compare the local recommendations (50 cm × 90 cm i.e., 2 plants per hill) with improved intercropping systems. All the 7 treatments had fertilizer applied at the same rate i.e., 20 kg P ha^{-1} and 50 kg N ha^{-1}, and the only differences were in crops grown (intercropping components) and their spatial arrangements. After the second season (in 2020), a farmer practice involving maize-pigeonpea intercrop was introduced to compare with treatments applied with inorganic fertilizers. Farmer practices did not receive inorganic fertilizers. The trials were researcher-designed and managed. Because of challenges in security of farmer fields (against communal grazing of fields at end of the season) three sites were dropped, and replaced i.e., two sites dropped in the second and one in the third year. Trials ended up being hosted in 9 sites between 2018 and 2021, however, since statistical analysis was done for each year *(more details in section 2.8)* data from all sites were included. In each site, treatments were replicated 3 times on plots measuring 7 m × 5 m (gross plot area). Also, in each site, treatments were separately randomized.

Maize, beans and pigeonpea were planted following farmer intercropping practices, DUL and Mbili-Mbili intercropping systems (Table 1; Fig. 1). In Mbili-Mbili, two consecutive maize rows were planted at a spacing of 0.25 m × 0.5 m and alternated with a 1.3 m space where two rows of pigeonpea and one row of beans were sown. Unlike MBILI which involved integration of two rows of a single legume species *(*Woomer et al., 2004*)*, Mbili-Mbili involves two species of legumes. For all cases, planting was conducted manually using hand hoes. Except for the treatment where Meru 513 maize variety was planted across the study period (i.e., treatment 7), Meru 515 was planted in 2018 and 2019 seasons, Syngenta 624 in 2020 and Dekalb 8031 in 2021. Bean variety in both DUL and Mbili-Mbili treatments was Jessica while pigeonpea was *ICEAP 00040* long duration variety. Studies (Myaka et al., 2006; Adu-Gyamfi et al., 2007; Hoeschle-Zeledon, 2019; Kihara et al., 2021; Mugi-Ngenga et al., 2021) have reported the suitability of the selected genotypes within smallholder systems in Babati. Decision of using Syngenta and Dekalb 8031 maize seeds was reached following a discussion with extension staff which was guided by the seasonal weather forecasts. Seed inoculation was not done for the legume component. In 2020 and 2021, a second bean crop was planted after harvesting the first bean crop, taking advantage of still low pigeonpea canopy.

Table 1
The treatments implemented in the assessment of system performance.

Treatment number	Treatment description
1	Sole maize – Doubled-up legume (DUL) rotation[¥]. Sole maize system had a spacing of 25 cm by 90 cm; Doubled-up legume had pigeonpea spaced at 50 cm by 90 cm and two rows of beans intercropped between pigeonpea rows. *Sole maize was cultivated in first season and rotated with Doubled-up legume*
2	Maize planted at 25 cm by 90 cm and intercropped with pigeonpea at 50 cm between maize rows. Maize *no de-topping*
3	Maize planted at 25 cm by 90 cm and intercropped with pigeonpea at 50 cm between maize rows. *Maize de-topped[β] at physiological maturity*
4	Doubled-up legume (DUL) – sole maize rotation[¥]. *Like Treatment 1 except that Doubled-up legume was cultivated in the first season and rotated with sole maize in the consecutive season*
5	Maize planted at 50 cm by 90 cm (maize 2 plants per hill) and pigeonpea at 50 cm between maize rows. *Maize de-topped[β] at physiological maturity*
6	Two rows of maize (planted at 25 cm 50 cm) intercropped with 1 row of beans sneaked between 2 rows of pigeonpea ("Mbili-Mbili intercropping"). *Bottom leaves of maize stripped[£]*
7	Meru 513. Maize planted at 25 cm by 90 cm and pigeonpea at 50 cm between maize rows. *No de-topping. Maize variety has vertical leaf architecture*
8	Farmer practice. *Maize intercropped with pigeonpea. System fully managed by farmers. No external nutrient amendments.*

[¥] Except for fields that were changed, cereal-legume rotation was consecutively repeated for four seasons.
[£] Removal of five bottom leaves of the maize plants at 50% silking.
[β] Removal of maize tops just above the ear at dough stage (R4 stage).

2.2. Field management practices

Fields were ploughed using tractors, the most common mode of land preparation for most smallholder farms in Babati. Planting usually commences in December through January, depending on the agroecological zone. Except for the farmer practices, maize in all plots received a uniform basal application of 20 kg P ha^{-1} of Minjingu Nafaka plus at sowing and later 50 kg N ha^{-1} of Minjingu Top-dressing fertilizer (from Minjingu Mines and Fertilizer Limited), 4 weeks after planting following fertilizer recommendations for the region (Kihara et al., 2021). Being compound fertilizers, Minjingu Nafaka plus with phosphorus (16% P_2O_5) is blended with N (9%), K (6%), CaO (25%), S (5%), MgO (2%), Zn (0.5%) and B (0.1%) while Minjingu Top-dressing has N (27%), P_2O_5 (10%) and CaO (15%). Weeding was conducted two times i.e., when maize had developed six (V6) and eleven (V11) leaves, using hand hoes.

2.3. Soil sampling and analyses

Soil sampling was done during the establishment of trials. Samples were collected from 0 to 20 cm depth at three spots from each replicate and mixed to form a homogeneous replicate-level sample for soil nutrient characterization. Chemical determination was conducted for total N and C by Duma type of combustion using CN elementar analyzer (Vagen et al., 2010) while available P, S, Cu, Zn, B, and Fe were extracted based on Mehlich-3 extraction (Mehlich, 1984) at the Crop Nutrition Laboratory in Nairobi. Soil pH was determined in water using a soil: water ratio of 1:2.5. Soils from the study sites were deficient in N and C indicating the need for application of both organic and inorganic fertilizers during crop production (Table 2). Soils in Riroda village had P, Zn and B levels below the recommended thresholds of 15 ppm (Nandwa and Bekunda, 1998), 1.5 ppm, and 0.5 ppm (Aref, 2011), respectively.

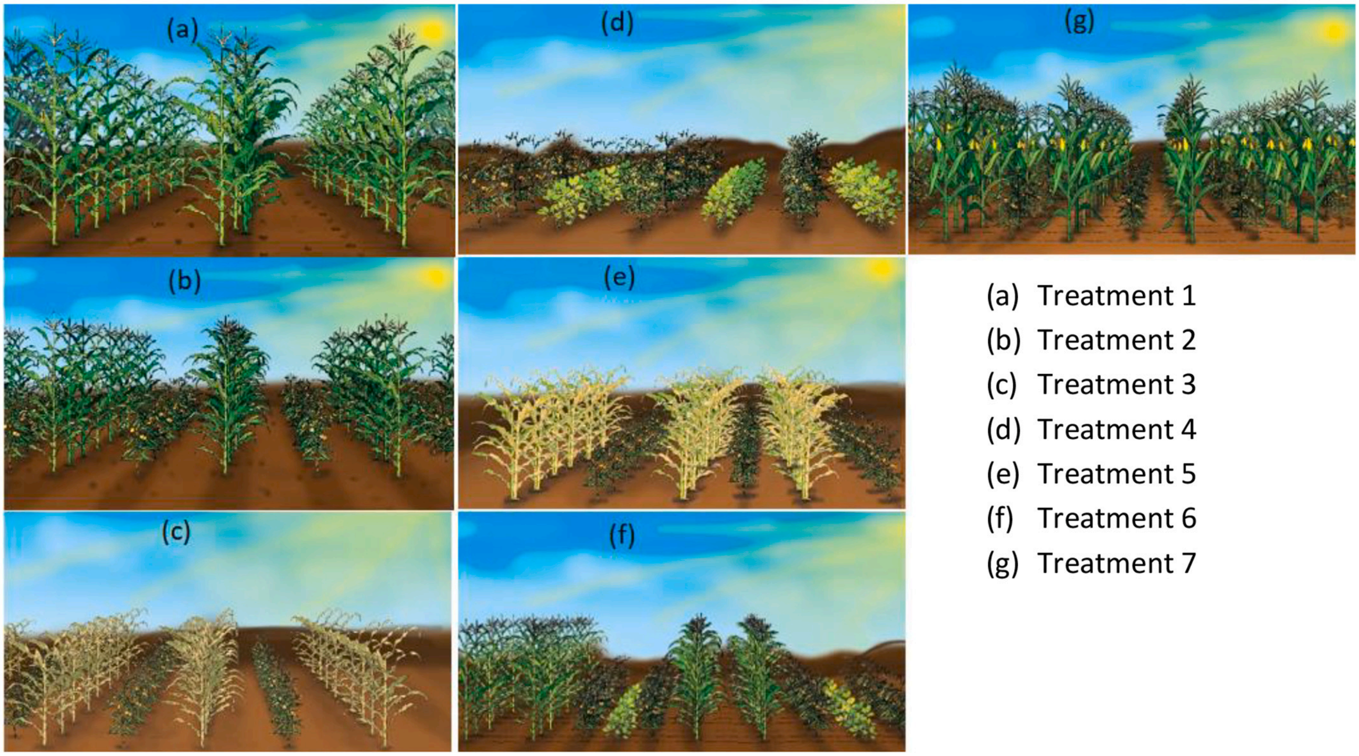

Fig. 1. Illustrations of improved intercropping options tested during 2018–2021 seasons in Babati, Tanzania.

Table 2
Soil chemical characteristics of experimental fields located in three sites of Babati District.

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

Values in brackets are standard deviations.

2.4. Stripping and de-topping activities

Maize stripping was conducted on Mbili-Mbili system at anthesis (i.e., 50% silking) by cutting five bottom leaves from the collar of the maize plants. Maize de-topping was conducted on treatments 3 and 5 at dough stage (R4 stage), i.e., before the young pigeonpea crop had started to flower. During this process, maize tops were chopped off at about 10 cm above the ear leaf. Field weight of total stripped leaves, topped maize biomass and their sub-samples were recorded and samples transported to Tanzania Agriculture and Research Institute (TARI) laboratory for oven drying (60 °C) and dry weight measurements.

2.5. Yield assessment

Yields of all the intercropping components were determined at physiological maturity, (R6 stage). Harvesting was conducted on net plots measuring 3 m × 3 m upon leaving out the guard rows to reduce border effects. Beans (i.e., harvested in March/April) were uprooted while maize (harvested in June/July) and pigeonpea (harvested in September/October) were cut at ground level, and field weights recorded. To estimate maize yield, cobs were manually separated from stovers and total weight of each yield component recorded. Representative cob and stover samples were collected by randomly selecting 5 cobs and stover (chopped and thoroughly mixed) and their field weights recorded (Kinyua et al., 2021). Pigeonpea and bean pods were also manually separated from haulms and both parameters weighed for field weight determination. In the laboratory, samples were oven dried at 60 °C for 24 h, after which both the pods and cobs were shelled. After drying both the grain and biomass samples of beans, maize, and pigeonpea to a constant moisture, their dry weights were recorded and used to calculate overall yields, at plot level, expressed on a per hectare basis (Matusso et al., 2013).

2.6. Economic assessment

Economic analysis was performed to assess the profitability of each cropping system under evaluation. Total variable cost (TVC) was calculated as the cumulative expenses during land preparation (ploughing and harrowing), purchase of inputs i.e., fertilizers and herbicides, conducting farm operations i.e., planting, weeding pest and disease control, topping, stripping, harvesting and post-harvest operations (Table 3). The cost of conducting different farm management practices was obtained from interviewing farmers and the local agricultural extension agent for each of the sites. Fertilizers and agrochemical prices were sourced from local agro-dealer outlets. Maize stover (including toppings and strippings), bean residues and pigeonpea husks were also included in the overall system economics since they are valued as livestock feed in the study area. Pigeonpea stalks are a major source of fuel for the farming households and were valued at per animal drawn cart basis. Prices were obtained in the local currency (Tanzanian shillings) and converted into US dollars (US$) using conversion rates for each cropping year where 1 US$ was trading at Tsh 2269 in 2018, 2251

Table 3
Cost of labor, inputs and farm gate prices of parameters used to calculate cropping systems' economics between year 2018 and 2021 in Babati, Tanzania.

Parameter	Price ranges (US$)
Maize seed 2 kg packet	5.2–5.3
Minjingu Nafaka per 50 kg bag	22.0–25.6
Minjingu Topdressing per 50 kg bag	55.5–61.5
Labor cost (US$ day^{-1})	1.8–2.6
Harvesting one 100 kg bag of maize grain	0.7–0.9
Harvesting one 120 kg bag of pigeonpea grain	2.5–3.0
Harvesting one 120 kg bag of bean grain	2.2–2.7
Cost of pesticides per hectare	16.2–54.9
Threshing one 100 kg bag of maize grain	0.4–0.5
Threshing one 120 kg bag of bean grain	1.1–1.4
Price of maize grain per 100 kg bag	15.2–43.6
Price of bean grain per 120 kg bag	52.9–127.3
Price of pigeonpea grain per 1 kg	0.2–0.5
Price of bean residues per 25 kg	0.9–1.2
Price of PP Stalks per 65 kg Cart	6.5–9.2

Note: Price ranges provided cuts across the study period.

(2019), 2283 (2020) and 2309 (2021). Costs that were the same across sites and years were US$ 0.4 for a kilogram of bean seed, US$ 0.3 for a kilogram of pigeonpea seed, US$ 1.1 for threshing a bag (120 kg) of pigeonpea grain, US$ 2.2 price of maize stover per 150 kg animal drawn cart, and US$ 1.1 price of pigeonpea husks per 25 kg bag *(all these are excluded in* Table 3*)*. Biomass from fallen leaves from Pigeonpea and beans were not valued in this study and could contribute to soil fertility benefits.

2.7. Farmer surveys

In the year 2019, a group of 120 farmers was purposively selected from the three villages (where trials were conducted) for participatory testing of Mbili-Mbili and DUL systems. The criteria for selection were farmer availability, willingness to test a new technology, household type (i.e., both male and female-headed households) and the age group each farmer represented. Farmers were requested to provide a 20 m by 30 m parcel of land (equivalent to 0.1 ha) for implementing one of the two technologies. Selected farmers were provided with inputs (seeds and fertilizers) and with technical backstopping from the researchers, and usual contact between farmers and extension staff was maintained to ease access to necessary agronomic support. Before technology implementation, farmers were trained on designing the two innovations and on general crop management. Annual field days were conducted on one of the two trials established in each of the three villages. Farmers who had implemented DUL in 2019 were more attracted to the implementation of Mbili-Mbili because of the maize component, therefore, DUL was dropped to suite farmer preferences. During the 2020 cropping season, the number of participating farmers increased to 150 and later to 225 in 2021. Farmers who joined the technology testing process in 2019 continued through the study period.

A survey was conducted at the end of the 2021 cropping season to assess how farmers adapted Mbili-Mbili technology to meet their household food demands and understand their experiences during implementation of the technology. The sample had more male than female farmers since male farmers typically control access and use of land in this study site and were keen to ensure their involvement in matters affecting their land. The survey targeted individual members of households who were main decision-makers and implementors of Mbili-Mbili and DUL technologies. This ensured that the actual members of households who directly interacted with the technologies were interviewed. Formal consents which entailed voluntary participation, confidentiality and anonymity of participant farmers were obtained before conducting interviews. Enumerators were locally recruited and trained.

2.8. Data analysis

Crop yield data were analyzed separately for the different cropping seasons because of some variations in treatments across the study period. The variations included: a farmer's practice introduced in 2020 and different maize varieties across the study period to suit the prevailing weather. Also, in 2020 and 2021, two bean crops *(*i.e.*, two bean phases)* were planted during the same cropping season as a further intensification of Mbili-Mbili and DUL. The second bean phase is associated with extra seeds as inputs and the cost of planting and field management (seeds and labor). For each year, the crop yield data were analyzed across all sites, with variates being the different yield components i.e., cereal and legume grains, stover (including toppings and strippings) and the haulms. The intercropping options were considered as the treatments while replicates and experimental sites were used as the blocking structure in GenStat software version 14. Where models were significant, means were separated using least significant difference (LSD) at $p \leq 0.05$.

Gross incomes (GI; $ ha^{-1}) were computed using farm gate prices of the crop produce. Net revenue (NR; $ ha^{-1}) was the difference between GI and TVC ($ ha^{-1}) (i.e., Gross Income – Total Variable Costs).

Stability analysis for the different systems under study across the different agroecological conditions and years was conducted using Shukla variance to help establish the most economically viable technology for recommending to farmers. Economic data was analyzed using R statistical software *(http://www.r-project.org/)* and GenStat software version 14 where the different economic parameters were considered as variates while factors within the model were the different cropping systems and years when the trials were conducted. The blocking structure was the three replicates and the different sites.

Survey data was subjected to descriptive analysis i.e., means, standard deviations, frequencies, and percentages, to identify the adaptations farmers made to Mbili-Mbili and their experiences during its implementation. Differential assets and rights analyses (Zhang et al., 2021) were used to explore whether assessment of technologies was affected by gender and household positions of Mbili-Mbili managers. This led to the establishment of three respondent categories: female managers in female-headed households (FHH), female managers in male-headed households (MHH) and male managers in male-headed households.

3. Results

3.1. Prevailing weather during the study

The amount and distribution of rainfall varied across the study period and at the different sites. The 2021 cropping season received the lowest rainfall (on average 404 mm), but with a good distribution, while 2019 had medium but poorly distributed rainfall (on average 542 mm) including in-season dry spells exceeding 2 weeks, few days after crop germination, for both sites (Fig. 2). The 2020 cropping season had an average rainfall of 1565 mm with a good distribution during the crop growth period while poor distribution in 2018 led to total loss of the bean crop. The 2021 cropping season had the highest average relative humidity (76.4%) while 2019 had the lowest (72.6%). Within the first four months of crop growth, relative humidity for the four seasons was in the order of 81.2%, 74.6%, 71.8% and 67.8% for the 2020, 2021, 2018 and 2019 cropping seasons, respectively. In addition, the average solar radiation levels were in the order of 109, 111, 114 and 121 W/m^2 for the 2020, 2018, 2021 and 2019 cropping seasons, respectively.

3.2. Yield

3.2.1. Maize yield

Site had significant effect on maize yields (data not shown). Except for the farmer practice which had significantly lower maize yields, there

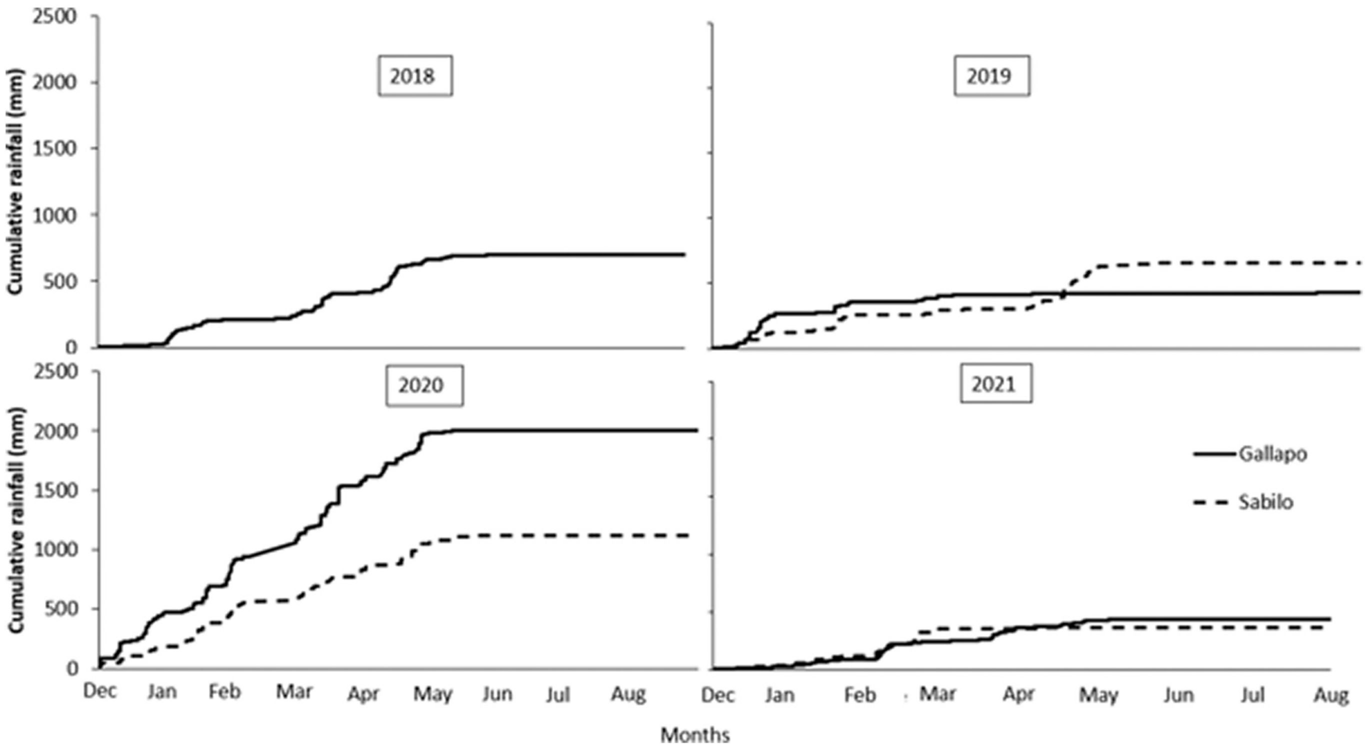

Fig. 2. Cumulative rainfall distribution recorded in Sabilo and Gallapo sites. Since weather stations had not been installed in the 2018 cropping season, rainfall data was obtained from NASA POWER (visit nasa.gov). The sites are within a 0.5 × 0.625-degree resolution i.e., within a 50 km radius, and the online data does not differentiate the climate data for the study sites.

were no significant yield differences across the other treatments except during 2021 when maize grain yields obtained from the DUL– sole maize rotation were higher ($P \leq 0.05$) than the maize with or without de-topping (Table 4). Mbili-Mbili system had similar maize yields as other cereal-legume intercropping practices. During the 2021 cropping season, de-topping had significantly higher maize stover yields relative to those with no de-topping.

Table 4
Mean maize grain and stover yield in different treatments between 2018 and 2021 in Babati, Tanzania.

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

[¥] Treatment involved a cereal-legume rotation consecutively repeated for four seasons.
[€] Treatment assessed only in the 2020 and 2021 cropping seasons.
[α] 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.

3.2.2. Pigeonpea yield

Significant treatment effects on pigeonpea productivity were observed in 2020 and 2021 cropping seasons. In the 2020 cropping season, DUL– sole maize rotation and the farmer practice had higher ($P \leq 0.05$) pigeonpea grain yield than the rest of the treatments. Also in 2021, DUL planted following a season of sole maize had the highest ($P \leq 0.05$) pigeonpea yield overall (Table 5). Mbili-Mbili treatment had similar pigeonpea yields (both grain and aboveground biomass) as other treatments that had maize as the main crop (i.e., excluding the system involving DUL).

3.2.3. Bean yield

Bean yields ranged from 0.12 t ha^{-1} in 2018 to 0.48 t ha^{-1} in 2021 in the Mbili-Mbili and 0.46 t ha^{-1} in 2019 to 1.28 t ha^{-1} in 2020 for the legume phase of DUL– sole maize rotation (Fig. 3). Bean yields from the DUL– sole maize rotation were 1.5 to 4 times more for haulms and 2 to 6 times more for grain than that of Mbili-Mbili system, depending on weather conditions in the different years.

There was a positive and significant relationship between pigeonpea grain yield and haulm yield with maize de-toppings and strippings across the 2019 and 2020 cropping seasons (Fig. 4). On average, pigeonpea grain yield increased (by 15.4%), with each ton of maize toppings/strippings, while the haulms increased by 94.3%. There are however diminishing returns of increased toppings on grain and haulm yields beyond toppings/strippings of 2.0 t ha^{-1}.

Table 5
Pigeonpea grain and biomass yields under different treatments as observed between the year 2018 and 2021 in Babati, Tanzania.

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

[¥] Treatment involved a cereal-legume rotation consecutively repeated for four seasons.
[€] Treatment assessed only in the 2020 and 2021 cropping season. Values within the same column and followed with different letters are significantly different.

3.3. Effects of treatments on system economics

Net revenue varied for the different cropping seasons, ranging from US$ -161 in 2018 to US$ 1438 in 2021 (Table 6). The legume phases of DUL– sole maize rotation had the lowest net revenues in the initial two cropping seasons (2018 and 2019) and yet by far the highest in 2021 where both pigeonpea and common beans had good yields. Mbili-Mbili had the highest net revenues in the 2019 (significantly higher than Maize 2 plants per hill and sole maize – DUL rotation; $P \leq 0.05$) and 2020 (significantly higher than Meru 513 and farmer practice; $P \leq 0.05$) cropping seasons. Like DUL– sole maize rotation, Mbili-Mbili also had significantly higher net revenues in 2021 relative to other practices. Sole maize – DUL rotation (starting with either maize or legume phase in the cropping season) had significantly lower total variable production costs (by US$ 100 to 250) than other treatments with improved management practices, however, farmer practice had US$ 80–120 less operational cost than the two rotational systems (Appendix A). Mbili-Mbili had lower ($P \leq 0.05$) total variable cost than the improved maize-pigeonpea system (i.e., Maize no de-topping) despite the integration of more intercropping components. While Mbili-Mbili was 21% and 55% more costly to plant, it was 49% and 57% cheaper to weed relative to Maize no de-topping and the legume phase of DUL- sole maize rotation, respectively.

Stability analyses based on Shukla variance showed sole maize - DUL rotation as having the highest overall mean net revenue ($653) while DUL- sole maize rotation had the lowest rank of net revenue and greatest variance across cropping seasons (both ranks on system's revenue summing up to 16; Table 7). Mbili-Mbili had the second highest overall mean net revenue ($623) and a lower variance. The most stable systems were the improved maize-pigeonpea system with de-topped maize and Mbili-Mbili. Mbili-Mbili had at least US$ 220 more revenue than the system where maize was de-topped, hence the best technology both in terms of economic performance and stability across variable weather among the tested intercropping options and for the study area.

3.4. Farmer adaptations to Mbili-Mbili in Babati: results of 2021 survey

Results indicated that 71.6% of the participants involved in this study were male managers from MHH, 16.6% female managers from MHH and 10.4% female managers from FHH. In the end, 89% of the 211 farmers tested Mbili-Mbili for one (49.3%), two (20.4%) or three cropping seasons (19%). Farmers who did not test Mbili-Mbili cited lack of enough technical capacity to implement (43.5%), high labor to implement at a critical period of the cropping phase (30.4%), diversion of inputs to other uses (8.7%) and lack of enough land (4.3%).

Ninety five percent of farmers who enrolled in 2021 (1 season of testing) and 2020 (2 seasons of testing) tested Mbili-Mbili in 0.1 ha of land while 41% of those who enrolled in 2019 had increased the area under Mbili-Mbili to between 0.2 and 0.4 ha. Farmers indicated increase in crop yield, profits, and intensification of production (multiple crops/ benefits) as the main reasons for expanding area under Mbili-Mbili. Overall, the number of crops tested by farmers were 2 (21% i.e.,

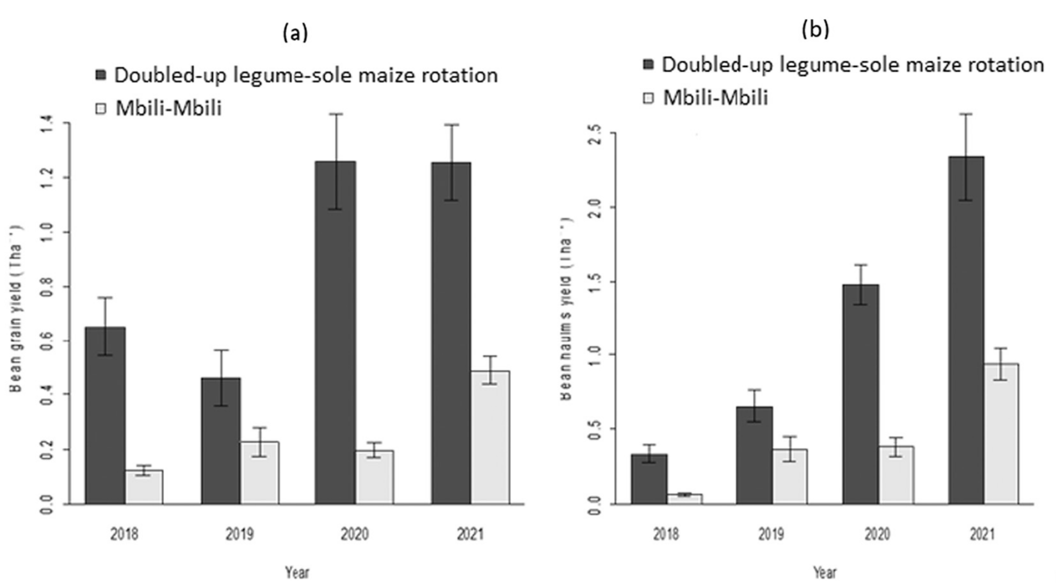

Fig. 3. Bean grain (a) and haulm yield (b) in Babati, Tanzania. The error bars represent 95% confidence intervals. Pair-wise error bars within one year that are not crossing are significantly different.

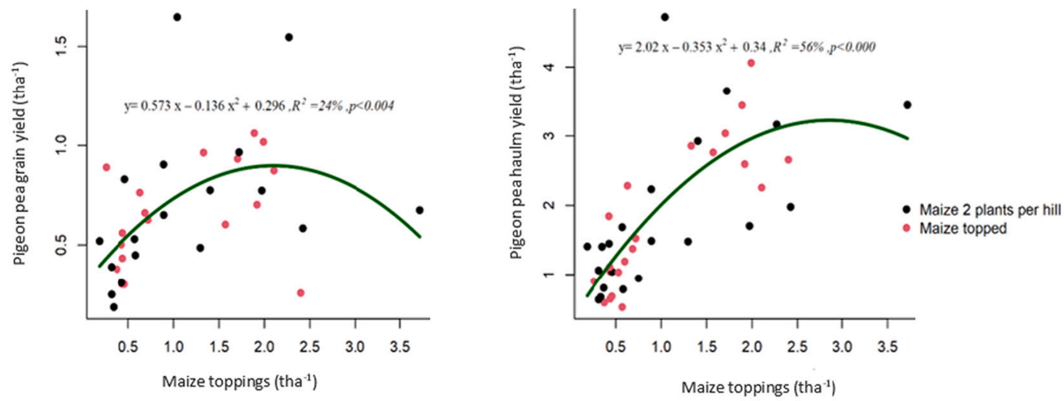

Fig. 4. Effect of maize de-topping on both pigeonpea grain and haulms yield during the 2019 and 2020 cropping seasons in Babati.

Table 6
Annual net benefits (US$) from the treatments implemented in Babati, Northern Tanzania between the 2018 and 2021 cropping seasons.

Treatment	2018	2019	2020	2021
Sole maize – DUL rotation¥	−46.7^{a}	37.1^{c}	1112.4^{a}	1438.3^{a}
Maize no de-topping	−16.3^{a}	291.3^{abc}	993.7^{a}	367.5^{cd}
Maize de-topped	−99.1^{ab}	207.1^{abc}	1155.6^{a}	498.9^{cd}
DUL– sole maize rotation¥	−160.6^{b}	342.7^{ab}	992.3^{a}	269.4^{d}
Maize 2 plants per hill	−79.5^{ab}	141.4^{bc}	969.6^{a}	577.9^{c}
Mbili-Mbili	−69.6^{ab}	418.0^{a}	1199.9^{a}	986.7^{b}
Meru 513	−16.7^{a}	320.3^{ab}	1107.7^{b}	519.9^{cd}
Farmer Practice€	–	–	412.8^{b}	524.2^{cd}
P-value	0.034	0.05	0.003	0.001
LSD	92.2	273.5	434.2	301.0

¥ Treatment involved a cereal-legume rotation consecutively repeated for four seasons.
€ Treatment assessed only in 2020 and 2021 cropping seasons. Value of maize leaf toppings and strippings were included in the treatment economics (statistical analysis). Values within the same column and followed with different letters are significantly different.

Table 7
Stability statistics on overall revenue for the treatments implemented in Babati, northern Tanzania between 2018 and 2021 cropping seasons.

Treatment	Overall mean net revenue (US$)	Shukla Variance	Rank of Revenue	Rank of Variance	Summation of ranks of revenue and variance
Sole maize – DUL rotation¥	653^{a}	52,565	1	7	8
Maize no topping	379^{b}	−2148	7	1	8
Maize de-topped	396^{b}	−1406	5	2	7
DUL– sole maize rotation¥	326^{b}	103,850	8	8	16
Maize 2 plants per hill	384^{b}	−1224	6	3	9
Mbili-Mbili	623^{a}	1338	2	5	7
Meru 513	454^{ab}	650	4	4	8
Farmer Practice*	468^{ab}	1609	3	6	9
P-value	0.01				
LSD	202.4				

¥ Treatment involved a cereal-legume rotation consecutively repeated for four seasons.
* Treatment not assessed for the first 2 cropping seasons hence not considered in overall stability discussions. Values within the same column and followed with different letters are significantly different.

MBILI) and 3 (79% i.e., Mbili-Mbili). Forty four percent of farmers divided the plot they implemented Mbili-Mbili into two portions to test a duo combination of 3 legumes (i.e., beans with cowpea (*Vigna unguiculata*) and beans with pigeonpea) that were provided by the project. When disaggregated by sex and household position of the participants, 50% of female managers in FHH, 45% of female managers in MHH and 43% of male managers in MHH tested at least three legume components under Mbili-Mbili technology. The rest of farmers (56%) did not plant one or more of the main leguminous intercrops i.e., cowpea, beans and pigeonpea, citing poor market for crop, delayed timing, seeds not available, or the crop species not fit for Mbili-Mbili system. Maize was the common cereal across all farms while legumes planted were beans (77%), cowpea (72%), pigeonpea (69%), lablab (*Lablab purpureus*; 2%), and groundnut (*Arachis hypogaea*; 2%). Sunflower (*Helianthus annuus*) was integrated by 2% while cassava (*Manihot esculenta*) and pumpkins (*Cucurbita* spp.) were also intercropped by 0.5% of the participants.

Forty two percent of farmers who were involved in testing of Mbili-Mbili system modified its design. Of the participants who modified the design, 56.4% modified the number of intercrops in Mbili-Mbili by either planting one (i.e., 34.6% planted beans, 6.4% pigeonpea and 2.6% cowpea) or more intercropped species. In addition, 55% either increased or reduced the number of rows of the intercrops, 2.6% planted a relay of lablab after harvesting beans, 1.3% alternated the different intercrops i.e., either cowpea, bean or pigeonpea, in each of the intra-row spaces of maize and 14% either reduced or increased spacing (inter or intra-rows) of the intercropping components. Both female managers from FHH and MHH had high preference for cowpea than bean and pigeonpea as an intercrop in Mbili-Mbili. Only 21% of female managers from both farmer categories did not plant cowpea in Mbili-Mbili compared to 31% for male managers in MHH (Table 8). While 43% of female managers from FHH did not plant beans, similar proportion (42%) of female managers from MHH did not plant pigeonpea. All farmers planted maize in proper rows, and 97% for the inter-cropped legumes. Forty one percent of female managers from FHH who implemented Mbili-Mbili modified the design by either increasing (18%) or reducing (12%) the number of plant rows relative to 8% and 10% of female managers in MHH and 7% and 20% of male managers in MHH, respectively. Of the 41% of female managers in FHH who modified Mbili-Mbili design, 57% planted multiple rows of a single legume species while the rest planted >2 intercrop species. Targeting a high income and improving household food security were cited as the main reasons for design modification.

Farmers who participated in technology testing reported 79% more maize grain yield in Mbili-Mbili than their usual systems. Farmers' observation on increased maize grain yield in Mbili-Mbili was consistent with results from researcher trials where yields increased by between 50 and 60% over the farmer practices. When maize yields of Mbili-Mbili implemented in farmer trials was compared to that of their usual

Table 8
Key modifications conducted by farmers testing Mbili-Mbili system in Babati between 2019 and 2021.

Modifications conducted on Mbili-Mbili design	Female managers in female-headed households (%)	Female managers in male-headed households (%)	Male managers in male-headed households (%)
Did not integrate beans	42.9	36.8	34.7
Did not integrate pigeonpea	35.7	42.1	33.7
Did not integrate cowpea	21.4	21.1	31.7
Increased no. of legume rows	17.6	6.7	7.0
Reduced no. of legume rows	11.8	10.0	20.1
Modified plant spacing	9.1	8.6	9.9

Proportion for crop omissions were generated from 14, 19 and 101 for female managers in Female-headed, female managers in Male-headed, and male managers in Male-headed, respectively, who failed to intercrop. The latter were obtained from the total population i.e., 22, 35 and 151 for female managers in FHH, female managers in MHH and male managers in MHH, respectively.

systems, a positive gain of up to 4 t ha^{-1} in maize yields was perceived by at least 80% of farmers who implemented Mbili-Mbili system and its modified versions (Fig. 5).

In two of the three villages where survey was conducted, 62.2% of farmers perceived that implementation of Mbili-Mbili was more labor intensive than farming as usual (Table 9). Contrary to the other villages, 61% of farmers in Riroda indicated that conventional system was more labor intensive than implementing Mbili-Mbili (Table 9). The reduced labor requirements in Mbili-Mbili cited by farmers in Riroda was consistent with findings from researcher trials where weeding labor was lower by $40 than in farmer practices. When labor demands of Mbili-Mbili was disaggregated by sex and household position, 55% of female managers in FHH, 74% of female managers in MHH and 62% of male managers in MHH indicated that there is increased labor relative to conventional systems.

Despite increased labor being reported, 97% of the farmers indicated willingness to scale up the area under Mbili-Mbili from 0.1 ha to between 0.2 and 0.4 ha (Fig. 6). Willingness to expand land allocation for the technology was reported at 0.24 ha by female managers from FHH, 0.32 ha by female managers from MHH and 0.36 ha by male managers from MHH. While all female managers in FHH were willing to scale up Mbili-Mbili, 3% of both the female managers in MHH and male

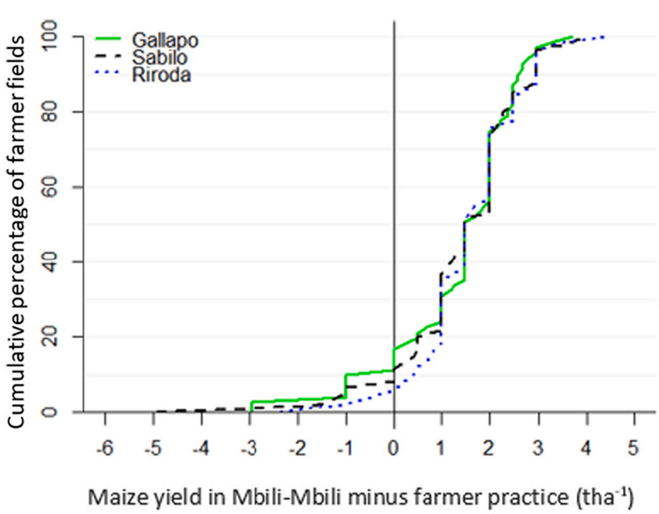

Fig. 5. Cumulative distribution of yield differences between Mbili-Mbili and the farmers' practice in Babati in 2021.

Table 9
Farm labor requirements by farmers (numbers) for implementation of Mbili-Mbili relative to local farmer practices as observed in Babati in 2021.

Perception of labor requirement	Female managers in female-headed households	Female managers in male-headed households	Male managers in male-headed households	Total
	Gallapo			
Equal for both technologies	0	4	15	19
High in conventional than Mbili-Mbili	2	0	2	4
High in Mbili-Mbili than conventional	6	14	30	50
	Riroda			
Equal for both technologies	0	0	2	2
High in conventional than Mbili-Mbili	5	5	22	32
High in Mbili-Mbili than conventional	1	4	14	19
	Sabilo			
Equal for both technologies	1	0	7	8
High in conventional than Mbili-Mbili	2	0	3	5
High in Mbili-Mbili than conventional	5	4	39	48

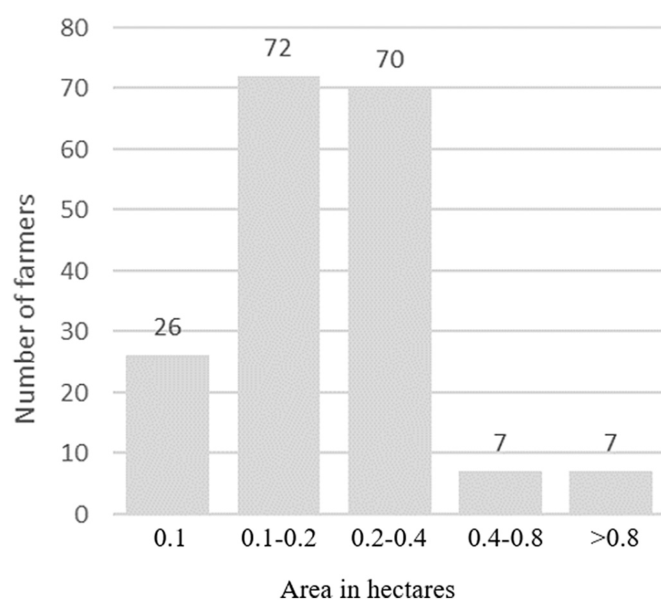

Fig. 6. Distribution of farmers and the land area in which they intend to implement Mbili-Mbili in Babati as reported in 2021.

managers in MHH were not ready to scale up the technology. This category of farmers cited amount of time and resources needed to implement Mbili-Mbili as the major hurdles to technology scaling. Ninety six percent of farmers indicated willingness to continue implementing Mbili-Mbili even without project support. Moreover, 90% of the farmers implementing Mbili-Mbili were willing to train other farmers, with 52% having already trained on average 4.2 (min = 1, max = 15, total = 88) other farmers. Of the 88 farmers who were trained by farmers in the project, only 24 implemented Mbili-Mbili on an average of 0.4 ha piece of land.

4. Discussions

Seasonal weather variation affects the attainable yield in rainfed smallholder systems like those of our study area. The landscape in Babati is characterized by undulating terrain which contributes to the existing rainfall, temperature, and soil fertility gradients (Kihara et al., 2015). The significance of the variable seasonal weather and gradients on crop production was visible where maximum maize grain yield of 2.0 t ha^{-1} and 6.2 t ha^{-1} were attained across the different seasons. Mugi-Ngenga et al. (2022) reported similar weather and topographical influences between 2018 and 2019 seasons in experimental sites within our study area where dry spells of between 40 and 70 days coinciding with vegetative development of maize and legumes were recorded. Soils in Riroda were also inherently deficient of P, Zn and B nutrients which are key in boosting crop productivity. However, Minjigu Nafaka Plus fertilizer (applied at sowing) is blended with micronutrients, which could have helped in moderating the associated deficiency. In addition, soils in Riroda have a sandy texture (67.3%) and low (12%) clay content (Mugi-Ngenga et al., 2022) which could have amplified the effects of weather, during the poor seasons.

Employing good agricultural practices such as plant spacing, and fertilizer have potential for doubling maize yields relative to common farmer practices in the study area. Similar results have been observed in the same region (Kihara et al., 2021) and in other parts of SSA (Mbanyele et al., 2021). Low yields under farmer practices can be attributed to low plant populations occurring when farmers broadcast seeds behind the plough (as a planting method; Mugi-Ngenga et al., 2021), and low application of organic and industrial fertilizers (Adu-Gyamfi et al., 2007; Kihara et al., 2015). The higher yields (50% on average) in improved practices compared to farmer practices demonstrate that proper spacing and soil fertility management such as through manure and/or fertilizer application are needed to improve crop productivity in the study area (Fanadzo et al., 2010). In the on-farm study by Kihara et al. (2015), manure application increased maize yield by up to 1.5 t ha^{-1}.

High legume productivity under DUL relative to that of maize-legume intercrops results from less competition for growth resources. Pigeonpea yield under the farmer practice was also higher (in 2020) than that of improved maize-legume systems. Low maize densities and productivity ($<$2.5 t ha^{-1}) observed in farmer practices in the study area (Kihara et al., 2015; Mugi-Ngenga et al., 2021) contribute to reduced competition for growth resources resulting in improved legume yields. Thus, the intercropping penalty of maize on yield of long duration pigeonpea observed by Myaka et al. (2006) is less severe when plant density of the maize is low.

Managing various aspects of production within intercropping (e.g., de-topping, striping and varying crop spacing) is important for reducing the penalty of the cereal to the legume. Although pigeonpea yields were not affected by de-topping of maize in our study and similarly also Mashingaidze et al. (2012), a relationship between topped biomass and pigeonpea productivity was established. De-topping and stripping of maize provide early light penetration to the intercropped legumes, initiating subsequent development phases such as early flowering (data not shown). Other studies have observed higher biomass and grain yields of legumes following stripping and de-topping. For example, Mañgaser (2013) reported Land Equivalent Ratio of 1.15 when maize was de-topped relative to LER of 1.04 with no de-topping. These practices worked for the bean and pigeonpea genotypes planted during this study. Therefore, more research is needed to assess the performance of stripped and de-topped systems under different genotypes. Maize toppings and strippings were used as foliage for feeding livestock. This practice can be exploited by farmers to generate foliage which can supplement fodder limitations during periods when outdoor grazing is restricted.

Rotation of maize sole crop system with DUL can be considered as a good strategy for replenishing soil nutrients in resource-constrained smallholder systems through nitrogen fixation and other soil health benefits including pest and disease suppressions (Smith et al., 2016; Mwila et al., 2021). This is especially important in the systems of our study area characterized by low application of both organic and inorganic fertilizer (Mponela et al., 2022; Mugi-Ngenga et al., 2021). The positive legume-cereal rotational benefits explain the consistent results of increased maize yields following rotation with the DUL. Significant yield increases of cereal following a legume rotation have often been reported (Pandey et al., 2017; Altieri et al., 2018; Tariq et al., 2019).

Risk is a key factor considered by farmers as important in guiding investment choices. Although sole maize - DUL rotations had very high net revenue in 2021, the system was also associated with high risk (i.e., high variance). High revenue under this system, unlike in the system where legume phase started, coincided with a season characterized by a well distributed rainfall. Seasons with both weather extremes i.e., high rainfall amounts with uneven distribution and those with in-season droughts had a yield penalty on the legume phase. Results from this study contradicts those of John et al. (2021) who reported DUL rotations to be more stable than both cereal-legume intercrops and sole systems involving both cereal (maize) and legumes (pigeonpea and groundnuts). Yield stability of DUL - maize rotations, in above study, can be attributed to the potential of pigeonpea and groundnuts to resist variable weather conditions relative to beans which are more vulnerable to extreme weather conditions. This indicates that targeting DUL, involving beans, to seasons with moderate and well-distributed rainfall could be beneficial to farmers in Babati. The attractiveness of the revenue generated by DUL might be driven by harvesting two bean crops within the same year in some cases, and the high and stable bean prices. Still, the low total variable costs for implementing the DUL phase (e.g., lower by up to US$ 300 per season relative to other systems) could be attractive especially when a farmer has little investment capital in specific years. Nevertheless, with still low reliability of climate predictions, DUL may not be an immediate choice by farmers.

Integration of maize, pigeonpea and beans within the same system, in Mbili-Mbili, not only provides high revenues but these are also more stable across seasons. Economic advantage of growing maize through maintaining a larger space of intercropped legume relative to conventional maize-legume systems has been demonstrated (Mucheru-Muna et al., 2010; Woomer, 2007). The increase in cropping area under Mbili-Mbili from year to year and the expressed intentions to scale indicate its preference by farmers. On the contrary, reduction of number of farmers who tested DUL by a third during the initial season and their shifting to Mbili-Mbili in the consecutive season after beans were damaged by in-season drought indicate farmers are unwilling to invest in technologies and management practices associated with high risk. A similar trend of farmers preferring maize-legume systems with either one or two legume rows over legume-legume systems was observed by Anders et al. (2020) in Malawi.

Farmer preferences are key towards adoption of practices. While farmers dropped DUL due to weather vulnerability of the bean component as mentioned already, integrating cowpea in Mbili-Mbili seemed attractive. Female managers from both FHH and MHH had higher preference for cowpea, a legume doubling as a leafy and grain vegetable, compared to male managers in MHH. The crops' low market value is a likely reason of its unattractiveness to male farmers who prefer pigeonpea and beans. The latter forms a major contributor to smallholder farmer incomes that are mainly controlled by men (Fischer et al., 2021). Contrasting findings were made in Malawi where cowpea is less preferred, for cereal-legume systems, by female farmers who cite taste and vulnerability to pest attack as major barrier to its adoption (Waldman et al., 2016). Unlike Babati, female farmers in Malawi preferred planting soybean and pigeonpea due to high yields, marketability, and access to seeds. However, adoption of cowpea can help to increase crop diversity, food security (Li et al., 2009; Snapp and Fisher, 2015), and food availability for longer periods due to staggered harvests, and reduced risk of total crop failure (Makate et al., 2016; Bowles et al., 2020).

Actual and perceived labour requirements influence farmer decisions on technology uptake. The need to source for additional manpower during planting and having to train laborers before laying out Mbili-Mbili was considered as both expensive and time consuming. Indeed, female managers from FHH indicated lower area for scaling Mbili-Mbili than other farmer categories. The willingness by MHH to expand land allocation (0.35 ha) more than FHH (0.24 ha) can be attributed to FHH owning smaller land holdings than those in MHH. In Babati and surrounding districts i.e., Kiteto and Kongwa, FHH own an average of 2.1 ha of land, which is 0.7 ha less than that of MHH (Fischer et al., 2017). The urge to increase household's food supply and income without support from a male head could also have contributed to female managers in FHH putting more focus on the benefits derived from Mbili-Mbili than its labor demands. Farmers' view on increased labor of a technology vis a vis its adoption concurs with Kassie et al. (2014) and Kanyamuka (2017) that adoption of a technology is a factor of farmers' perception on its labor demands.

The high labor requirements during implementation of Mbili-Mbili, as reported by 22% of farmers, can be attributed to the accuracy and precision required at the time of planting. When compared to farmer practices where planting is by broadcasting seeds behind animal/tractor drawn plough, a fast and simple technique for covering a unit land (Mugi-Ngenga et al., 2021), Mbili-Mbili require proper spacing, achieved through line planting. More laborers are also required to plant three crop species at a defined spacing relative to two species all sown along the same plough line under farmer practices. The increased labor demands of Mbili-Mbili were consistent with Woomer et al. (2004) who reported 20% more labor during implementation of MBILI than in conventional intercropping systems. However, farmers associated Mbili-Mbili with lesser weeding time and ability to weed rapidly within the properly spaced rows which reduces its overall variable cost. High labor demand is a potential constraint to uptake/adoption of Mbili-Mbili, as it is for other improved management practices in SSA (Mrema et al., 2018). The level of mechanization in this region is also reported to be much lower than other regions of the world (Schuler et al., 2016; Dahlin and Rusinamhodzi, 2019) with animal draught and engine powered machines contributing only 15% of the total farm labor in the SSA region (AUDA-NEPAD, 2019). If Mbili-Mbili is to be adopted more widely with prospects of expansion in acreage per household, it would be necessary to explore the use of locally assembled prototypes of planters to reduce planting labor.

5. Conclusion

This study unveils different intercropping options that can be adapted to improve legume production in smallholder farming systems. Practicing DUL system has less investment capital (US$ 100–300) which makes it more affordable by resource poor farmers than improved maize-pigeonpea systems. The system generates high revenues in some years i.e., by up to 430% but is risky and vulnerable to changing weather. Implementing Mbili-Mbili results in gain of US$ 623 which is higher than the other maize-pigeonpea intercropping systems (< US$ 600). The agronomic and economic performance of this system is stable across climate/weather and is recommended for uptake by farmers in Babati and similar environments in Hanang and Arusha Districts. In addition, stripping of lower maize leaves provides 15% more pigeonpea grain, 94% haulms and nearly 1 t ha^{-1} of biomass that can be preserved for use as livestock feed at critical periods of the year. Farmer adaptation of Mbili-Mbili demonstrate a wide scope of its redesigning to suite their food production and income needs. Labor is the main hurdle for scaling Mbili-Mbili across the different household typologies in Babati. Therefore, addressing labor challenge, i.e., through mechanization, is important to promote adoption and scaling of Mbili-Mbili.

Declaration of Competing Interest

Authors have no competing interests to declare.

Data availability

Data will be made available on request.

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Appendix A. Overall total variable cost from the treatments implemented in Babati, Northern Tanzania between 2018 and 2021 (US$)

Treatments	Year			
	2018	2019	2020	2021
Sole maize-DUL rotation	548.5^{c}	421.5^{e}	638.4^{d}	546.0^{d}
Maize no de-topping	617.6^{a}	561.4^{b}	698.1^{b}	718.3^{b}
Maize de-topped	616.5^{a}	578.5^{a}	732.6^{a}	750.4^{a}
DUL-sole maize rotation	387.2^{d}	502.0^{d}	493.6^{e}	654.7^{c}
Maize 2 plants per hill	628.0^{a}	566.8^{ab}	707.5^{b}	746.8^{a}
Mbili-Mbili	581.1^{b}	532.5^{c}	679.9^{c}	726.8^{ab}
Meru 513	618.5^{a}	561.4^{b}	706.6^{b}	730.5^{ab}
Farmer Practice	–	–	408.3^{f}	427.8^{e}
P-Value	0.001	0.001	0.001	0.001
LSD	25.7	13.4	16.7	23.9

Values in a column followed by different letters are significantly different. Farmer practice was not assessed in 2018–2019 seasons.

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