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Comparative effects of legume-based intercropping systems involving pigeon pea and cowpea under deep-bed and conventional tillage systems in Malawi

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Abstract

Leguminous-based intercropping, combined with conservation agriculture, is a promising approach to improve soil fertility, crop yields, and sustainable land use for smallholder farmers in sub-Saharan Africa, including Malawi. This study aimed to assess the effects of incorporating legume-based intercropping systems involving pigeon pea (*Cajanus cajan*) and cowpea (*Vigna unguiculata*) into the deep bed farming (DBF) system promoted by Tiyeni in northern Malawi. The study used a split plot design with cropping systems (CS) as the main plots and tillage systems (TS) as the sub-plots. All treatments were replicated three times. The study encompassed two cropping seasons, where CS included legume-based treatments, sole cropped maize (*Zea mays*) without fertilizer (MZ) and sole cropped maize with 92 kg top dressing N fertilizer per hectare (MZ + 92), while TS included DBF and conventional tillage (CT). The study found that all plots with leguminous crops on both DBF and CT showed higher levels of ammonium (NH_4^+), nitrate (NO_3^-) and phosphorus (P) in the soil, but DBF had significantly higher levels over 2 years. Intercropping systems showed higher land productivity (land equivalent ratio > 1) than sole cropping in both years, indicating that legume-based cropping can improve land use efficiency and yields. It can be noted from this study that intercropping systems based on cereals and legumes, implemented in DBF, has the potential to sustain agricultural intensification in sub-Saharan African countries where access to chemical fertilizers is limited among smallholder farmers.

1 | INTRODUCTION

Climate change, declining soil fertility, and food insecurity continue to pose a challenge to sustainable agriculture throughout sub-Saharan Africa (SSA) (Eze et al., 2020). One important strategy to address these challenges is the development and adoption of climate resilient farming systems (Altieri et al., 2015; Fagbemi et al., 2023). Cardoso et al. (2013) state that the climate resilience of agricultural systems depends on soil properties such as structure, nutrient content, organic matter (OM), and biota. Intercropping, crop rotation, and other mixed cropping systems (CS) that allow

Abbreviations: CA, conservation agriculture; CP, cowpea; CS, cropping systems; CT, conventional tillage; DBF, deep bed farming; LER, land equivalent ratio; MoAFS, Ministry of Agriculture and Food Security; MZ, maize; PP, pigeon pea; SSA, sub-Saharan Africa; TS, tillage systems.

for more efficient use of agricultural resources are among the agricultural practices associated with sustainable crop production (Iqbal et al., 2018). As an example, multiple studies have revealed that intercropping maize (*Zea mays*) with legumes leads to a land equivalent ratio (LER) > 1, implying that cultivating maize and legumes together is more beneficial in terms of agricultural resource use efficiency and grain yields than growing them in separate fields (Kamara et al., 2019; Njira et al., 2021; Yilmaz et al., 2008). There are several reasons why intercropping maize with legumes may lead to a higher LER. For one, legumes are known to fix nitrogen (N) from the atmosphere into the soil, which can benefit the growth of maize (Sharma & Behera, 2009). Additionally, intercropping can create a more diverse and complex ecosystem, which can help to suppress weeds, reduce pest and disease pressure, and improve soil health (Leoni et al., 2022; Roohi et al., 2022). In sub-Saharan African countries, including Malawi, maize is the main crop grown mono-culturally under conventional tillage (CT) as the staple food. It is traditionally planted in November and harvested in April (main rainy season) year by year (Badu-Apraku & Fakorede, 2017). Recently, however, studies have shown that persistent monocropping negatively affects the diversity and activity of soil microorganisms, soil fertility, and thereby crop yields (F. Li et al., 2020). According to Tsiafouli et al. (2015), increased agrochemical use, land conversion, agricultural expansion, and agricultural specialization have had adverse effects on the environment and led to loss of habitat and biodiversity, pollution and eutrophication of water bodies, increased greenhouse gas emissions, and reduced soil quality. These impacts have resulted in decreased productivity and increased vulnerability of agricultural systems to climate change and other environmental challenges (Habig et al., 2015). This has prompted growing concerns about the environmental sustainability of agriculture, as well as food security and how to maintain crop yields, especially among poorer populations on marginal lands that have no access to agricultural inputs (Devkota et al., 2022). In response, a range of agroecological approaches, not least conservation agriculture (CA), have emerged over the last four decades as potential ways to promote sustainable agricultural intensification (Kassam et al., 2014; Thierfelder et al., 2013; Mkomwa & Kassam, 2022).

CA is an approach to farming that involves minimal soil disturbance, permanent soil cover, and diversified CS (Bhan & Behera, 2014). It aims to promote the ecological functions of soil and agroecosystems by reducing soil erosion, improving soil health, and increasing water and nutrient retention (Mgolozeli et al., 2020). CA is based on three principles: minimal soil disturbance (little or no-tillage), maintaining permanent soil cover (at least 30%), and diversified crop association/crop rotation, or intercropping (Farooq & Siddique, 2015). By following these principles, CA farmers can achieve higher yields and greater resilience to environmental challenges while reducing their reliance on synthetic fertilizers and pesticides (Kassam et al., 2014). This has generated further interest in the potential contribution within CA of legume-based intercropping or crop rotation systems, due to their reported positive impacts on soil conservation, soil fertility, and crop yields, that can decrease reliance on fertilizer and labor inputs (Chen et al., 2011; Martin-Guay et al., 2018; Yuan et al., 2012). According to Batista et al. (2016) and da Silva et al. (2017), intercropping systems, especially those that incorporate leguminous crops, can improve soil fertility and yield as well as reduce per unit cost of the product. Moreover, several studies have suggested that inclusion of legumes in intercropping can contribute more to soil fertility in no-till systems compared to CT systems (Huang et al., 2008). In no-till systems, such as CA, where soil disturbance is minimized, legumes are able to establish and fix nitrogen more effectively due to improved soil moisture retention and reduced soil erosion (Derpsch et al., 2010). On the other hand, in CT systems, where soil is heavily disturbed, legumes may struggle to establish and fix nitrogen effectively. Tillage can disrupt the soil structure, reduce soil moisture, and cause nitrogen loss through denitrification and leaching (Kumar et al., 2020).

One of the key benefits of implementing the principles of CA is the ability to improve soil health (Sithole et al., 2016). By reducing soil disturbance and maintaining permanent soil cover, CA practices promote the growth of beneficial microorganisms and OM in the soil. This results in increased soil fertility, water retention, and nutrient cycling, which in turn improves crop yields and reduces the need for chemical inputs (Friedrich et al., 2012; Huss et al., 2022). In addition, CA practices can help to reduce greenhouse gas emissions by sequestering carbon in the soil (Alam et al., 2019). Another advantage of CA is its ability to improve biodiversity (Hobbs, 2007). By promoting a diversity of crops and maintaining permanent soil cover, CA practices can provide habitat and food for a wide range of organisms, including beneficial insects and wildlife (Sithole et al., 2016). This can help to reduce the

Core Ideas

- Tiyeni's deep bed farming (DBF) in Malawi reports significant increases in maize crop yields.
- Impacts of leguminous intercropping (pigeon pea and cowpea) in DBF and conventional tillage (CT) plots are compared.
- Intercropping increases soil fertility in DBF and CT, but levels are significantly higher in DBF after 2 years.
- Intercropping within DBF can enhance food security and support sustainable agriculture.

need for chemical pesticides and promote natural pest control. Despite these benefits, CA is not without its challenges (Giller et al., 2009). Adopting CA practices can require significant changes to traditional farming practices and may require additional investments in equipment and training (Johansen et al., 2012). In addition, the benefits of CA may not be immediately apparent, and farmers may need to wait several years before seeing improvements in soil health and crop yield. According to Friedrich et al. (2009), when CA is adopted, it is usually abandoned within 5 years because farmers feel progress is taking too long. However, studies have shown that the long-term benefits of CA can outweigh these challenges, leading to increased productivity and profitability for farmers (Erenstein et al., 2012; Thierfelder & Mhlanga, 2022). The growing challenges of climate change and limited access to agricultural inputs have highlighted the need for even more innovative and effective techniques to be explored and implemented in SSA, and the deep bed farming (DBF) system promoted by Tiyeni in Malawi, is one such example (Mvula & Dixon, 2021).

Unlike many forms of CA, Tiyeni's DBF initially requires deep tillage using either a pick-axe or hoe (double-digging) to a depth of 30 cm in order to break the hard pan of the subsoil that is ubiquitous throughout northern Malawi. This promotes deeper root growth, soil aeration, easier percolation of water, and the construction of deep beds that follow the contours of the land to reduce vulnerability to rapid runoff and severe soil erosion. Raised beds are 30-cm high, 1-m wide, and typically 15-to-25-m long (Tiyeni, 2023). Adjacent furrows are 50-cm wide on top and 30-cm wide at the bottom. Furrows are closed every 15–25 m, and box ridges are constructed to reduce runoff and increase rainwater infiltration, thus further preventing soil erosion from the field. Where furrows are closed, these areas are used as footpaths across the field. To avoid the formation of rills and gullies, furrow ends are raised above the level of the surrounding fields. This prevents water from draining in and out. Both footpaths and field boundaries are 50-cm wide and slightly above the beds (Tiyeni, 2023). Once the deep bed is constructed, it is recommended to avoid treading on the beds to prevent soil compaction for a period of 5 years (cultivation beds are usually reconstructed after 5 years). All crop residues after harvest are returned to the deep bed as mulches. Although evidence suggests that the DBF system makes a significant contribution to soil and water conservation through reduced runoff and soil erosion (Mvula, 2021), and enhanced maize yields are also reported in many DBF farmers' fields (Mvula & Dixon, 2021), the impacts of legume-based intercropping systems under the DBF are not well understood. This study aimed to evaluate the effects of incorporating legume-based intercropping systems involving pigeon pea (*Cajanus cajan*) and cowpea (*Vigna unguiculata*) into the DBF system on soil nutrients and grain yield.

2 | MATERIALS AND METHODS

2.1 | Description of study site

The research was conducted in Msongwe on the outskirts of Mzuzu city, located on the Viphya plateau in northern Malawi, and the study site was located at 11°28′27.21″S 34° 3′29.20″E at an altitude of 1320 m above sea level. The area experiences an average annual rainfall of approximately 1280 mm, with temperatures ranging from 10°C in winter to as high as 32°C in summer. The area is characterized by Alisols soil type (Lowole, 1987). During the research, a total annual rainfall of 1315 mm was recorded in the first year and 1422 mm in the second year.

The area is mainly comprised of resource-poor smallholder farmers who rely on subsistence farming, which is predominantly rain-fed mono-cropping agriculture. Farming practices in this area are typically marked by clearing the land through the cutting down of trees, slashing of grasses, and burning, followed by making ridges, which are then followed by planting crops on ridges year after year. During lean periods of the year when farming income is insufficient, charcoal production is a common activity to generate extra income, although it is illegal (Wood & Thawe, 2013) and can lead to soil degradation and deforestation. The primary crops cultivated by farmers in the area include maize, cassava, beans, bananas, and soybeans, with maize being the staple food. Although farmers grow beans, soybeans, and groundnuts, few have attempted to cultivate other leguminous crops in their fields. It is worth noting that pigeon pea and cowpea have not been grown in this specific site prior to this study.

A farmer who was willing to participate and had not previously adopted DBF practice in the area was selected to implement both DBF and CT plots on their farm. Baseline soil properties were collected from a soil depth of 0–20 cm, revealing NH_4^+ levels of 21.43 mg/kg, NO_3^- levels of 11.98 mg/kg, and available P levels of 17.65 mg/kg. These pre-experiment analyses provided a benchmark for evaluating the comparative effects of the two tillage systems (TS).

2.2 | Experimental design and treatment description

A 2-year field experiment was conducted using a split plot design with three replications during the 2020–2021 and 2021–2022 CS (Figure 1). The experiment consisted of seven CS as the main plots: sole cropped maize without fertilizer (MZ), sole cropped maize with 92 kg top dressing N fertilizer per hectare (MZ + 92), sole cropped cowpea (CP), sole cropped pigeon pea (PP), intercrop of pigeon pea and maize (PP + MZ), intercrop of cowpea and maize (CP + MZ), and

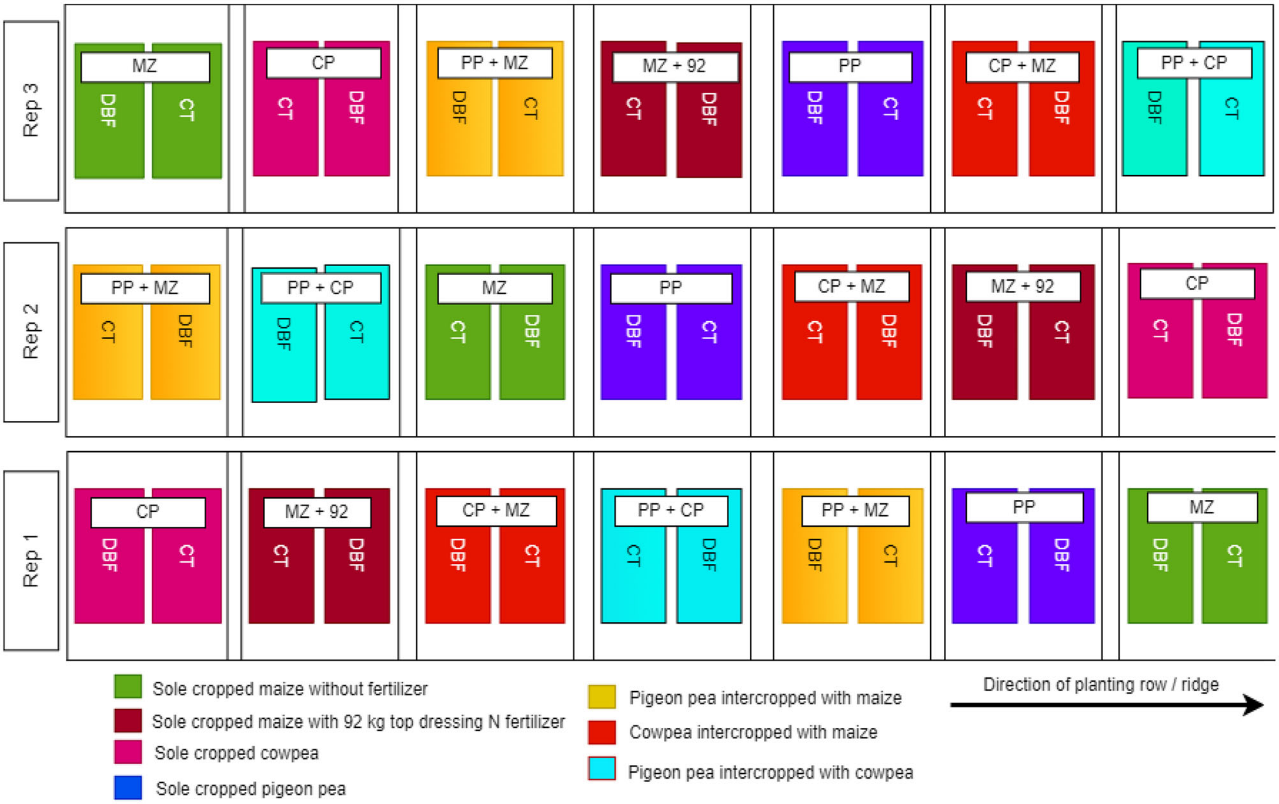

FIGURE 1 Diagrammatic representation of the experimental design and plots layout for the 2-year study. The main plots consisted of seven different cropping systems, with the sub-plots focusing on two tillage systems, deep bed farming (DBF) and conventional tillage (CT).

intercrop of pigeon pea and cowpea (PP + CP). The two TS were used as subplots: DBF and CT. To ensure consistency, the same crop/crops planted in the whole plots in 2020–2021 were planted in the same whole plot in 2021–2022. For example, if a whole plot was planted with maize intercropped with pigeon pea (PP + MZ) in 2020–2021, the same crop combination was planted in the same plot in 2021–2022. The subplots (TS) were divided into two groups, with one group of subplots maintained as DBF across the 2 years and the other group maintained as CT across the same period. The double cropping across two consecutive seasons aimed to evaluate the effects of the intercropping and TS over a longer period of time and determine if any observed effects were consistent across multiple growing seasons. This design reflects the common practice among smallholder farmers in the region of repeating their cropping from 1 year to the next, but it also seeks to shed further light on reports of declining yields following the first year of DBF cultivation (Mvula & Dixon, 2021). By maintaining consistency in the same crop/crops planted in the whole plot across the 2 years, the study was able to evaluate the effects of the different legume-based CS and TS on the same crop/crops in both years.

Each treatment plot measured 8 m by 3.5 m. The plot containing CT systems had 10 ridges of 3.5 m long, spaced at 75 cm apart, and the plot containing DBF had five beds of 3.5 m long with two rows each spaced at 75 cm apart. In both sole and intercrop, three seeds of pigeon pea were planted per planting station at a distance of 90 cm from each planting station and 75 cm between rows, according to the standard of Ministry of Agriculture and Food Security (MoAFS) (2012). In-row intercropping was similarly undertaken, according to MoAFS (2012), by planting either maize or cowpea between the pigeon pea planting stations on the row or ridge. In sole cropped cowpea, two seeds were planted per planting station at a distance of 20 cm between stations within the ridge or row and at 75 cm between ridges or rows, whereas the intercropped cowpea was planted at the same distance of 20 cm, which put three planting stations in every distance between two pigeon pea (PP) planting stations. As in the case of pigeon peas, three seeds of maize were planted per station at a distance of 90 cm from each planting station within the ridge or row and at 75 cm between rows or ridges in both sole stand and intercrop. The result was that the pigeon pea planting stations were systematically placed in the center of the spaces between maize planting stations in the intercrop of maize and pigeon pea planting model. The study involved planting Mkanakaufiti (IT99K-494-6), a cowpea resistant to *Alectra vogelii*; Mwayiwathu alimi (ICEAP 00557), a medium-duration pigeon pea; and Mkango (SC 653), a medium-duration maize variety.

2.3 | Plant growth and determination of yields

Plant height and harvesting were conducted within a defined net plot area of 6.5 m x 2.5 m, which was obtained by leaving 1 m as guard space from the side of the 8 m x 3.5 m gross plot. This was done as a standard procedure to avoid outside interference. Maize plant height data were gathered during the critical tasseling stage of growth. During the harvest, yields of all three crops were accurately recorded. Additionally, the count of maize ears per plant and the weight of 1000-maize grains were determined. Different crop species in these experiments reached maturity at different periods of the season and, therefore, were harvested at different periods. Cowpeas were harvested first, then maize, and finally pigeon peas. While this study focused on harvest-related traits and was designed to offer insights into the factors influencing crop yields, we recognize the limitation of this study that other factors likely influence grain yield, not least physiological traits, and stress response mechanisms; future research could explore these additional traits and offer a more holistic understanding of crop performance under different conditions.

2.4 | Assessment of productivity of the cropping systems

2.4.1 | Land equivalent ratios

LER was used in this study to measure the productivity of various CS. LER is the amount of land needed to grow a sole crop to the amount of land required to intercrop crops at the same level of management to produce the same grain yield or economic output. To calculate LER, the yields of intercropped crops were divided by the net yield of each component crop, and the results were added together. LER of 1.0 means that the land area needed to grow a component crop in an intercrop is the same as when growing a component crop in a pure stand. On the other hand, an LER > 1.0 indicates an advantage in intercropping, while an LER < 1.0 indicates a disadvantage of intercropping. The result of dividing each component crop before summing up to get LER is called partial LER. Dhima et al. (2007) state that the partial LER indicates which component crop is more competitive than the other in exploiting resources. The component crop that has more competitive advantage will have a higher partial LER than the other. The LER and partial LER are calculated as Dhima et al. (2007) stated algebraically in Equation (1) as follows:

$$\mathrm{LER} = \mathrm{LER_A} + \mathrm{LER_B}, \tag{1}$$

where

$$\mathrm{LER_A} = \mathrm{YA_B}/\mathrm{Y_A},$$

$$\mathrm{LER_B} = \mathrm{YB_A}/\mathrm{Y_B}$$

Here, A and B are crop species under mono-cropping or intercropping. $\mathrm{Y_{AB}}$ is grain yield of crop A in an intercrop with crop B, and $\mathrm{Y_{BA}}$ is grain yield of crop B in an intercrop with crop A. Y_A and Y_B are grain yields of sole crop A and crop B, respectively.

2.4.2 | Soil sampling and analysis

Soil samples were collected at depths of 0–20 cm in each plot using a soil auger, based on the simple random sampling during both years after harvest. The soil at the same depth of 0–20 cm was sampled from three points per plot and combined into composite samples. The soil samples were then air-dried for analysis of available P. Moist soils were used for analyzing nitrate (NO_3^--N) and available ammonium (NH_4^+-N). Available P was determined using Mehlich-3 method (Anderson & Ingram, 1989), whereas ammonium (NH_4^+) and nitrate (NO_3^-) were determined using colorimetric technique (Anderson & Ingram, 1989).

2.4.3 | Data analysis

The collected data were subjected to Genstat 19th edition statistical package for split plot analysis of variance. To determine significant differences, the least significant difference was employed at a significance level of 5%. In addition, the productivity of various CS was mainly assessed and evaluated using LER and partial LER.

3 | RESULTS

3.1 | Effects of cropping systems and tillage systems on available nutrients

3.1.1 | Nitrate

There were significant differences ($p < 0.001$) in the levels of available nitrate (NO_3^-) as influenced by both the CS and TS in both years (Table 1a,b). The treatments that contained leguminous crops grown in both DBF and CT showed significantly higher ($p < 0.001$) available nitrate than those that

TABLE 1 Nitrate (mg kg^{-1} soil) as influenced by both cropping systems and tillage systems.

Tillage systems	MZ	MZ + 92	CP	PP	PP + MZ	CP + MZ	PP + CP	Mean (TS)
A: Cropping systems (2020–2021)								
Deep bed	11.26	12.70	14.84	15.18	14.72	15.23	16.79	14.39b
Conventional tillage	10.63	11.54	14.14	13.20	13.90	13.99	15.21	13.23a
Mean (CS)	10.95a	12.12a	14.19b	14.31b	14.49b	14.61bc	16.00c	
F pr (CS)	<0.001				$LSD_{0.05}$(CS)	1.41		
F pr (TS)	<0.001				$LSD_{0.05}$(TS)	0.24		
Fpr (CS × TS)	0.061				CV (%)	2.7		
B: Cropping systems (2021–2022)								
Deep bed	13.61	13.80	17.47	18.84	18.72	19.23	21.42	17.58b
Conventional tillage	10.26	11.03	16.23	15.30	16.54	16.08	17.35	14.68a
Mean (CS)	11.93a	12.41a	16.85b	17.07b	17.63b	17.66b	19.39b	
F pr (CS)	0.014				$LSD_{0.05}$(CS)	4.15		
F pr (TS)	<0.001				$LSD_{0.05}$(TS)	0.87		
F pr (CS × TS)	0.605				CV (%)	8.1		

Note: Means with different letters are significantly different.
Abbreviations: CP, cowpea; CS, cropping system; CV (%), coefficient of variation; F pr, F probability; $LSD_{0.05}$, least significant difference at 5% significant level; MZ, maize sole cropped without inorganic fertilizer; MZ + 92, maize sole cropped and supplied with 92 kg N ha^{-1}; MZ + CP, maize intercropped with cowpea; MZ + PP, maize intercropped with pigeon pea; PP, pigeon pea; PP + CP, pigeon pea intercropped with cowpea; TS, tillage systems.

had sole maize without fertilizer and sole maize with 92 kg N ha^{-1} during both years. In the first year, the treatment with PP + CP intercrop had significantly higher ($p < 0.001$) amount of nitrate than the rest of the treatments. The treatment that contained CP + MZ showed an overlapping effect between the treatment that contained PP + CP and other treatments with leguminous crops. In the second year, all treatments that contained legumes showed significantly higher ($p = 0.014$) available nitrate. However, the treatment that contained PP + CP showed slightly higher available nitrate than all other treatments that contained leguminous crops. All treatments grown on DBF showed significantly higher ($p < 0.001$) available nitrate (NO_3^-) than those treatments grown on CT. Available nitrate (NO_3^-) was not affected by CS × TS interaction during both 2020–2021 and 2021–2022 growing seasons.

3.1.2 | Ammonium

The results of the analysis indicate that there were significant differences ($p < 0.05$) in the levels of ammonium (NH_4^+) as influenced by both CS and TS during both growing seasons (Table 2a,b). Compared to the treatments that contained sole maize crop without fertilizer (MZ) and sole maize crop with 92 kg of nitrogen per hectare (MZ + 92), the treatments that incorporated leguminous crops exhibited significantly higher levels of ammonium (NH_4^+) with $p < 0.001$ and $p = 0.003$ in 2020–2021 and 2021–2022, respectively. In the first year, the treatment with PP + CP intercrop exhibited significantly higher ($p < 0.001$) in ammonium ($NH4^+$) content compared to the rest of the treatments. In the second year, all treatments with leguminous crops revealed significantly higher ($p < 0.003$) in ammonium ($NH4^+$) content. However, the treatment with PP + CP had slightly higher ammonium ($NH4^+$) content compared to all other leguminous crop treatments. All treatments grown on DBF exhibited significantly higher in ammonium ($NH4^+$) content compared to treatments grown in CT with $p < 0.001$ and $p = 0.004$ in 2020–2021 and 2021–2022 cropping seasons, respectively. The ammonium (NH_4^+) content was not impacted by the interaction of CS and TS during both growing seasons. The treatments with sole maize crops without fertilizer (MZ) and sole maize crops with 92 kg N ha^{-1} (MZ + 92) grown on both DBF and CT showed significantly lower in ammonium (NH_4^+) content compared to the rest of the treatments.

3.1.3 | Available phosphorus

The results show that there were no significant differences ($p < 0.096$) in the levels of available phosphorus (P) as influenced by the CS in the first year (Table 3a). However, plots that contained leguminous crops grown under both DBF and CT exhibited slightly higher levels of available P compared to those that contained only maize without fertilizer (MZ) and maize with 92 kg N ha^{-1} (MZ + 92). In the second year (2021–2022 growing season), there were significant differences ($p < 0.027$) in available P as influenced by CS (Table 3b). The treatments that contained pigeon pea and cowpea (PP + CP), pigeon pea (PP), cowpea (CP), pigeon pea and maize (PP + MZ), and cowpea and maize (CP + MZ) grown under both DBF and CT showed significantly higher

TABLE 2 Ammonium (mg kg^{-1} soil) as influenced by both cropping systems and tillage systems.

Tillage systems	MZ	MZ + 92	CP	PP	PP + MZ	CP + MZ	PP + CP	Mean (TS)
A: Cropping systems 2020–2021								
Deep bed	20.22	24.13	31.56	29.97	29.55	29.44	35.89	28.68b
Conventional tillage	15.14	16.05	23.89	24.92	22.89	24.45	32.40	22.82a
Mean (CS)	17.68a	20.09a	27.72b	27.44b	26.22b	26.94b	34.15c	
F pr (CS)	<0.001				$LSD_{0.05}$(CS)	5.53		
F pr (TS)	<0.001				$LSD_{0.05}$(TS)	2.38		
F pr (CS × TS)	0.916				CV (%)	13.9		
B: Cropping systems 2021–2022								
Deep bed	24.63	21.91	37.60	36.55	36.02	35.57	40.62	33.27b
Conventional tillage	13.44	19.91	32.29	31.14	30.47	32.19	33.44	27.56a
Mean (CS)	19.04a	20.91a	34.95b	33.85b	33.25b	33.88b	37.03b	
F pr (CS)	0.003				$LSD_{0.05}$(CS)	8.64		
F pr (TS)	0.004				$LSD_{0.05}$(TS)	3.60		
Fpr (CS × TS)	0.843				CV (%)	17.9		

Note: Means with different letters are significantly different.

Abbreviations: CP, cowpea; CS, cropping system; CV (%), coefficient of variation; F pr, F probability; $LSD_{0.05}$, least significant difference at 5% significant level; MZ, maize sole cropped without inorganic fertilizer; MZ + 92, maize sole cropped and supplied with 92 kg N ha^{-1}; MZ + CP, maize intercropped with cowpea; MZ + PP, maize intercropped with pigeon pea; PP, pigeon pea; PP + CP, pigeon pea intercropped with cowpea; TS, tillage systems.

TABLE 3 Available P (mg kg^{-1} soil) as influenced by cropping systems and tillage systems.

Tillage systems	MZ	MZ + 92	CP	PP	PP + MZ	CP + MZ	PP + CP	Mean (TS)
A: Cropping systems 2020–2021								
Deep bed	19.35	19.81	25.04	23.61	25.06	25.53	27.44	23.69b
Conventional tillage	15.20	16.53	23.28	23.22	20.46	19.69	22.92	20.19a
Mean (CS)	17.28 ns	18.17 ns	24.16 ns	23.41 ns	22.76 ns	22.61 ns	25.18 ns	
F pr (CS)	0.096				$LSD_{0.05}$(CS)	6.05		
F pr (TS)	0.006				$LSD_{0.05}$(TS)	2.30		
F pr (CS × TS)	0.844				CV (%)	15.8		
B: Cropping systems 2021−2022								
Deep bed	19.69	20.17	27.71	28.48	29.39	29.53	34.44	27.06b
Conventional tillage	15.87	16.20	23.95	23.27	22.79	24.36	24.26	21.53a
Mean (CS)	17.78a	18.18a	25.83b	25.87b	26.09b	26.94b	29.35b	
F pr (CS)	0.027				$LSD_{0.05}$(CS)	7.23		
F pr (TS)	<0.001				$LSD_{0.05}$(TS)	1.25		
F pr (CS × TS)	0.101				CV (%)	7.7		

Note: Means with different letters are significantly different.

Abbreviations: CP, cowpea; CS, cropping system; CV (%), coefficient of variation; F pr, F probability; $LSD_{0.05}$, least significant difference at 5% significant level; MZ, maize sole cropped without inorganic fertilizer; MZ + 92, maize sole cropped and supplied with 92 kg N ha^{-1}; MZ + CP, maize intercropped with cowpea; MZ + PP, maize intercropped with pigeon pea; ns, nonsignificant; PP, pigeon pea; PP + CP, pigeon pea intercropped with cowpea; TS, tillage systems.

levels of available P compared to the treatments that contained only maize without fertilizer (MZ) and maize with 92 kg N ha^{-1} (MZ + 92). All treatments grown under DBF showed significantly higher levels of available P compared to those grown under CT (Table 3a,b). There was no interaction effect between CS and TS on available P during both the 2020–2021 and 2021–2022 growing seasons.

3.2 | Effects of cropping systems on maize yield components

The study examined the effects of different CS on various yield components of maize, including plant height, ear grain number, and 1000-grain weight. In the first year of the study, there were no statistically significant differences ($p = 0.051$)

TABLE 4 Maize plant height, ear grain number, and 1000-grain weight as affected by cropping systems.

Crop	Cropping system	Plant height (cm)		Ear grain number		1000-Grain weight (g)	
		2020–2021	2021–2022	2020–2021	2021–2022	2020–2021	2021–2022
Maize	MZ	144.5 ns	210.0a	335.5b	384.2a	363.4a	368.3a
	PP + MZ	187.2 ns	234.4b	318.2a	357.7a	398.7b	487.1b
	CP + MZ	157.3 ns	211.1a	317.8a	356.7a	407.2b	414.5a
	F pr	0.051	0.006	0.011	0.057	0.038	0.006
	LSD	34.49	14.92	12.24	25.10	34.50	65.9
	CV%	17.0	5.5	3.1	5.5	7.1	12.5

Note: Means with different letters are significantly different according to LSD at 5% significant level.
Abbreviations: CP, cowpea; CV, coefficient of variation; F pr, F probability; $LSD_{(0.05)}$, least significant differences at 5%; MZ, maize; PP, pigeon pea; ns, nonsignificant.

in maize plant height across different CS (Table 4). However, maize plants in the intercrop of PP + MZ exhibited slightly greater height (p = 0.051) compared to the intercrop of CP + MZ, and both intercrops showed taller plants compared to sole cropped MZ. In the second year, maize plants in the intercrop of PP + MZ significantly surpassed (p = 0.006) those in the intercrop of CP + MZ and sole cropped MZ in terms of height. Similarly, maize plants in the intercrop of CP + MZ were slightly taller than those in sole cropped MZ.

Regarding maize ear grain number per plant, significant differences (p = 0.011) were observed among CS in the first year. Sole cropped MZ had significantly more ear grain number (p = 0.011) compared to intercrops of PP + MZ and CP + MZ, with the intercrop of PP + MZ showing a slightly higher number than CP + MZ. However, in the second year, no significant difference (p = 0.057) was found in ear grain number, although sole cropped MZ exhibited a slightly higher number compared to intercrops of PP + MZ and CP + MZ.

The 1000-grain weight of maize grains showed significant differences (p = 0.038 and p = 0.006, respectively) across CS in both years. In the first year, intercrops of PP + MZ and CP + MZ exhibited significantly higher (p = 0.038) 1000-grain weights compared to sole cropped MZ. In the second year, the intercrop of PP + MZ had significantly higher (p = 0.006) 1000-grain weight compared to intercrop of CP + MZ and sole cropped MZ. While there was no significant difference between the intercrop of CP + MZ and sole cropped MZ, CP + MZ showed a slightly higher 1000-grain weight compared to sole cropped MZ.

TABLE 5 Yields of pigeon pea, cowpea, and maize as affected by cropping systems.

Crop	Cropping systems	Yields (kg ha^{-1})	
		2020–2021	2021–2022
Pigeon pea	PP	1035.5b	1532b
	PP + CP	799.7a	969a
	PP + MZ	813.3a	1064a
	F pr	0.004	0.007
	LSD	98.0	198.4
	CV %	5.5	10.5
Cowpea	CP	953.5b	1187.7b
	CP + PP	677.5a	735.3a
	CP + MZ	683.0a	731.8a
	F pr	0.003	<0.001
	LSD	106.79	29.14
	CV %	5.2	4.8
Maize	MZ	4788 ns	6110 ns
	MZ + PP	4168 ns	5802 ns
	MZ + CP	4004 ns	5342 ns
	F pr	0.063	0.329
	LSD	665.9	1243.8
	CV %	3.1	5.8

Note: Means with different letters are significantly different according to LSD at 5% significant level.
Abbreviations: CP, cowpea; CV, coefficient of variation; F pr, F probability; $LSD_{(0.05)}$, least significant differences at 5%; ns, nonsignificant.

3.3 | Effects of cropping systems on yields (kg ha^{-1})

The results of the impact of CS on grain yield are shown in Table 5. In both years, the grain yield of sole pigeon pea (PP) was significantly higher (p = 0.004 and p = 0.007, respectively) than that of pigeon pea in the intercrops of PP + CP and PP + MZ. Similarly, the grain yield of sole cowpea (CP) was significantly higher (p = 0.003 and $p < 0.001$, respectively) than that of cowpea in the intercrops of CP + PP and CP + MZ. Furthermore, even though no significant differences (p = 0.063 and p = 0.329, respectively) were observed, the grain yield of sole maize (MZ) was slightly higher than that of maize in the intercrops of MZ + PP and MZ + CP.

TABLE 6 Land equivalent ratios (LERs) and partial LERs.

	Partial values of LERs						LER	
	2020–2021			2021–2022			2020–2021	2021–2022
Cropping systems	Pigeon pea	Cowpea	Maize	Pigeon pea	Cowpea	Maize	LER	LER
PP + CP	0.77	0.71	N/A	0.63	0.62	N/A	1.48	1.25
PP + MZ	0.79	N/A	0.87	0.69	N/A	0.95	1.66	1.64
CP + MZ	N/A	0.71	0.84	N/A	0.62	0.87	1.55	1.49

Note: In the table, data are presented as mean values of indices and therefore are unit-less. LER > 1 implies that intercropping is advantageous.
Abbreviations: CP, cowpea; MZ, maize; N/A, not applicable; PP, pigeon pea.

3.4 | Land equivalent ratios and partial LERs

Table 6 indicates that the highest grain yield productivity was achieved when maize was intercropped with pigeon pea in both years, according to the LERs calculated. The benefits of intercropping over sole cropping were as follows: 66% by PP + MZ, 55% by CP + MZ, and 48% by CP + PP intercropping systems in the first year, and 64% by PP + MZ, 49% by CP + MZ, and 25% by PP + CP intercropping systems in the second year. Within an intercrop, to check which component crop was more competitive than the other in exploiting resources, the partial LERs (Table 5) show that PP was more competitive when intercropped with CP. On the other hand, maize showed higher partial LERs when intercropped with either PP or CP, which means it was more competitive than the partner component crops. Furthermore, in both cases of intercropping CP with either MZ or PP, CP produced lower partial LERs than the partner component crops, which implies it was less competitive.

4 | DISCUSSION

The higher values of nitrate (NO_3^--N) in treatments that contained legumes in both years when respectively compared to treatments that contained sole maize without fertilizer (MZ) and sole maize with 92 kg N ha^{-1} (MZ + 92) and pre-planting values, can be attributed to the nitrogen fixing effects of legumes and decomposition of their residues. Legumes fix atmospheric nitrogen through a symbiotic relationship with Rhizobia bacteria, which results in an increase in soil nitrogen levels (Gogoi et al., 2018). This nitrogen is then available for plant uptake and can result in higher levels of nitrate in the soil (Herridge et al., 2008). Additionally, leguminous crop residues contain high levels of nitrogen, which can be mineralized and released into the soil as the residues decompose (Palm et al., 2001). The findings of this study are consistent with previous research that has shown that the incorporation of legumes in CS can lead to increased nitrate (NO_3^--N) levels in the soil (Ghosh et al., 2008). Additionally, Ordóñez-Fernández et al. (2018) found that leguminous crops in both no-till and TS produced high nitrate (NO_3^-) content, with further improvement in the second season due to the decomposition of crop residues. Hayat et al. (2008) also reported the highest levels of NO_3^--N in the soil profile (0–120 cm) in treatments containing leguminous crop (bean) during both years of their experiment. Including legumes in an intercrop increases nitrogenase activity as well as improves soil fertility for sustainable agriculture (Fatima et al., 2007).

On the other hand, the higher levels of nitrate (NO_3^--N) in DBF compared to CT can be attributed to the incorporation of principles of CA into DBF. These CA principles, such as the retention of crop residues in the soil during deep-bed construction, may have effectively enhanced soil fertility by replenishing additional nutrients to the soil (Habig et al., 2015). According to Tiyeni (2021) and Mvula (2021), farmers practicing DBF regularly report improved soil fertility and crop yields often more than twice that of maize under CT. Practicing CA using permanent raised beds with crop residue retention is also effective in conserving soil and preventing soil degradation (Govaerts et al., 2007). It is important to note that DBF is also characterized by incorporation of manure application and mulching. Given this, together with the biological nitrogen fixation effects of leguminous crops, the improvements can occur from the first year of implementation. For example, Binacchi et al. (2022) found that the inclusion of cowpea in intercrop improved mineral nitrogen (NO_3^--N and NH_4^+ -N) content in CA to a slightly greater extent than in CT plots. Manure and crop residues, which are typically introduced in the first year of DBF, return large amounts of organic carbon and nitrogen to the soil (Reckling et al., 2014).

Similarly, the higher available NH_4^+ in treatments with legumes in both years can be attributed to the ability of legumes to fix atmospheric nitrogen through their symbiotic relationship with Rhizobia bacteria and the presence of high nitrogen content in the legume crop residues (Phiri & Njira, 2022). The highest available NH_4^+ in treatments with pigeon pea and cowpea (PP + CP) in the first year and the slightly higher available NH_4^+ in treatments with pigeon pea and cowpea (PP + CP) than other treatments containing legumes can be attributed to the combined effects of pigeon pea and cowpea. In the similar study, Njira et al. (2017) reported that the total nitrogen in the pigeon pea and cowpea (PP + CP) intercrop was the result of the addition of nitrogen contributed by each of the component crop in the intercrop. Also, Phiri and Njira (2022), in another study, reported that high available NH_4^+ in PP + CP treatments was due to the combined effects of addition of NH_4^+ contributed by decomposition of each of the component crop residues. The lowest values of NH_4^+ were observed in sole cropped maize and sole maize plus 92N fertilizer grown in both DBF and CT. This may be due to the fact that cereals cannot easily fix biological N and that their crop residues contain relatively small amount of N (Yan et al., 2020). On the other hand, cereal crop residues are of poor quality and are known to increase N immobilization, often due to their wide C/N ratios (Brennan et al., 2013). For instance, microorganisms that decompose carbon-rich and nitrogen-poor residues require more nitrogen for metabolic breakdown than N present in residues, so growing microbes will use more nitrogen (NO_3^--N and NH_4^+-N) present in the soil for their metabolism (Z. Li et al., 2019).

The higher levels of NH_4^+ in DBF can be attributed to the fact that it incorporates principles of CA, and as such, significantly improves soil microbiological activity (Habig et al., 2015), thereby increasing the decomposition of crop residues than with CT. In a similar study, Nascente and Crusciol (2013) reported higher levels of available NH_4^+ and NO_3^- in cover crop plots under CA than those under CT. Similar results were also obtained by de Oliveira (2010), where straw of *Brachiaria brizantha* contributed to an increase in soil N levels in no-till systems. According to Rosolem et al. (2010), when crop residues decompose, ammonium (NH_4^+) is formed first, but due to the moisture, presence of oxygen, pH, and temperature stability in CA, the activity of bacteria that transform ammonium to nitrate is favored, and therefore, ammonium is transformed faster into nitrate than in CT. This demonstrates the reason why both ammonium and nitrate are found in greater amounts in DBF than in CT.

The higher amount of available P in the plots that contained leguminous crops can be attributed to various mechanisms, one of which is the release of organic acids from legume root exudates (Dakora, 2003). As legumes grow, they release organic acids through their root exudates that bind to aluminum (Al) and iron (Fe) in the soil, resulting in the solubilization of native P and an increase in its availability in the soil for plant uptake (Gogoi et al., 2018; Marschner et al., 2011). Several studies have shown that the release of organic acids by legumes can significantly increase the availability of P in soils (Bagayoko et al., 2000; Jemo et al., 2006; Nuruzzaman et al., 2006). In addition to chelating Al and Fe, these organic acids can also directly release P from soil minerals and enhance microbial activity in the rhizosphere, further increasing the release of P (Archana et al., 2013). Furthermore, legumes have the ability to form symbiotic relationships with nitrogen-fixing bacteria known as rhizobia, which can provide a direct source of nitrogen for the plants (Maróti & Kondorosi, 2014). This nitrogen fixation process is energetically costly, and as a result, legumes allocate a significant proportion of their carbon to root exudation to attract and support the rhizobia. This root exudation can also enhance the release of organic acids, further contributing to the solubilization of P in the soil (Gogoi et al., 2018). Moreover, when legume crop residues decompose, they release large amount of organic P and high amount of organic acid anions and phenolics into the soil. The organic acid anions increase P availability in the soil solution by competing with phosphate ions for sorption sites on the soil particles (Kaur et al., 2016). In a similar study, L. Li et al. (2007) reported that faba bean in maize–faba bean intercrop highly increased amount of available P in the soil which later increased P acquisition and the grain yield per unit area of the maize row by 23.9% and 49.0%, respectively, and of the faba bean row by 37.3% and 22.0%, respectively, in P-deficient calcareous soils for 4 years of field experiment. This is consistent with the findings of Darch et al. (2018), who discovered that barley–legume intercropping resulted in 10%–70% higher P accumulation and 0%–40% greater biomass compared to monocultures, which led to the conclusion that barley–legume intercropping holds significant potential for sustainable production systems, particularly in low soil P conditions.

4.1 | Land equivalent ratio and partial LERs

All intercropping systems within the study provided yield advantages and all component crops were compatible with each other. This was reflected in the LER values, which were higher for all three intercrops (PP + CP, PP + MZ, and MZ + CP) than that of sole crops in both years. In particular, the intercropping of maize and pigeon pea achieved the highest LER in both years, meaning that more land would be required for monoculture to produce the same yield as the intercropping system—66% and 64% in each year, respectively. These results are in agreement with that of Njira et al. (2021) and Mhango (2011), who also reported that intercropping maize with pigeon pea gave highest LER. LER values were higher in all the intercrops than 1, indicating the advantage of intercropping over sole stand in regard to use of land or environmental resources for plant growth and development. This similar case was reported where cowpea was intercropped with maize (Yilmaz et al., 2008).

The higher partial LERs of maize showed that maize was more competitive than pigeon pea and cowpea in the intercrop and that maize utilized the N fixed by both pigeon pea and cowpea for better growth, development, and yields (Ogutu et al., 2012). Partial LER values also indicated that PP was more competitive than CP in PP + CP intercrop, and that CP was less competitive than both maize and pigeon pea. This similar case was reported where maize was intercropped with pigeon pea and cowpea (Njira et al., 2021), and the author found that the higher partial LERs in maize compared to pigeon pea and cowpea were due to maize's taller height, which shades the cowpea, and its fast growth habit, which allows it to out-compete the pigeon pea, which is known for its early slow growth. To sum up, maize benefited from residual nitrogen fixed by both pigeon pea and cowpea. This is an indication that three crops are also compatible as their growth stages for competition for growth factors do not overlap (Daryanto et al., 2020).

5 | CONCLUSION

This study has provided evidence that maize can successfully be intercropped with both pigeon pea and cowpea, and that this intercropping system not only provides the yield advantages of intercropping, but also allows for optimal utilization of the available environmental resources. When compared to standalone maize crops, intercropping maize with either pigeon pea or cowpea led to improved maize yields. In particular, intercropping maize with pigeon pea resulted in slightly higher maize grain yields than in the maize–cowpea intercrop. It was also noted that maize tended to dominate both pigeon pea and cowpea, as indicated by the partial LERs.

This concurs with a large body of empirical evidence suggesting that legume-based intercropping systems can significantly enhance soil nutrient levels and improve crop yields. Critically, through its incorporation of these practices alongside the principles of CA, Tiyeni's DBF system arguably offers an effective means of achieving sustainable agriculture. The implications of this are considerable; through the relatively small adaptations to smallholder farming systems that DBF brings, subsistence farmers in Malawi and beyond can benefit from a significant increase in crop yields, food security, and environmental sustainability. In the wider context, therefore, this study presents a key contribution to our understanding of sustainable and climate-smart agricultural systems.

AUTHOR CONTRIBUTIONS

Augustine Talababi Phiri: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; writing—original draft. **Keston Oliver Willard Njira**: Conceptualization; formal analysis; investigation; methodology; supervision; writing—original draft; writing—review and editing. **Alan Dixon**: Writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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