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## ORIGINAL ARTICLE

Agrosystems

# Deep bed farming with maize–soybean intercropping improves maize yield and soil fertility in northern Malawi

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## Abstract

In sub-Saharan Africa smallholder farmers face challenges of declining soil fertility, erratic rainfall, low crop yields, and food insecurity. Deep bed farming (DBF), a conservation agriculture-based approach promoted by Tiyei in Malawi, shows potential to address these issues. This study evaluated the effects of integrating maize (*Zea mays*)–soybean (*Glycine max*) intercropping with DBF on maize grain yield and soil fertility. A split-plot design was used, with cropping systems (CSs) as main plots and tillage systems (TSs) as subplots, replicated three times across three cropping seasons. CS included mono-maize without fertilizer (M), mono-maize with 92 kg N ha<sup>-1</sup> (M + 92 N), mono-soybean (S), and maize–soybean (MS) intercropping; TS comprised DBF and conventional tillage (CT). In season two, mono-maize without fertilizer was planted across all plots; in season three, maize was planted with 50 kg N ha<sup>-1</sup>. Results showed that MS intercropping under DBF significantly enhanced early maize growth—taller plants, more leaves, and greater leaf area compared to both mono-cropped maize under DBF and all CSs under CT. While M + 92 N yielded the most grain, intercropping showed favorable land productivity (land equivalent ratio > 1.16). Soybean yields were lower in intercrops but improved under DBF. Residual benefits from combined legume-based systems and DBF led to significantly higher maize yields and improved total N, available P, and soil organic carbon in subsequent seasons. Integrating MS intercropping with DBF enhances land-use efficiency and soil fertility, offering a climate-smart, conservation-aligned strategy for sustainable smallholder farming in Malawi and similar agroecological zones.

**Abbreviations:** ANOVA, analysis of variance; CA, conservation agriculture; CS, cropping system; CT, conventional tillage; DBF, deep bed farming; LER, land equivalent ratio; MS, maize–soybean; NGO, non-governmental organization; SOC, soil organic carbon; TGW, 1000-grain weight; TS, tillage system.

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### Plain Language Summary

Farmers in Malawi face declining soil fertility and low crop yields, severely impacting their food security. To combat these issues, deep bed farming (DBF), which maintains the health of the soil and conserves water, offers a promising solution. This study explored the differences in crop yield and soil fertility between DBF plots containing only maize and plots with maize intercropped with soybean. It also compared the performance of DBF to traditional agriculture that relies on continuous tillage. We found that (a) DBF boosted maize yields and soil fertility compared to traditional agriculture, and (b) there were further significant benefits where maize was intercropped with soybean. Land productivity was 21% higher in intercropped DBF plots compared to intercropped traditional agriculture plots. Combining DBF with soybean intercropping presents a sustainable approach to improving food security among smallholder farmers in Malawi and potentially throughout the region.

## 1 | INTRODUCTION

Smallholder farmers in sub-Saharan Africa, including those in Malawi, face acute challenges that constrain their agricultural productivity (Nyambo et al., 2022). These challenges include prolonged dry spells, declining soil fertility, erratic rainfall patterns, and limited access to essential inputs such as fertilizers and quality seeds (Alexandridis et al., 2023; Bogale & Bekele, 2023; Mbene et al., 2023). As a result, crop yields remain low, threatening food and nutrition security for large portions of the population (Junaid et al., 2024; Wang, 2022). In Malawi, for instance, average maize (*Zea mays*) yields typically range from just 2 to 3 t ha<sup>-1</sup>, depending on seasonal conditions—well below what is needed to meet the demands of the country's rapidly growing population (Muoni et al., 2024). These challenges underscore the urgent need for sustainable agricultural practices that can enhance crop productivity while improving soil health (Barrett, 2021).

One promising pathway for improving soil fertility and boosting yields among smallholder farmers is the adoption of conservation agriculture (CA) practices (Miah et al., 2023; Ngoma et al., 2021; Rodenburg et al., 2021; Thierfelder et al., 2015). CA is based on three core principles: minimal soil disturbance, permanent soil cover, and diversified cropping systems (CSs), such as intercropping or crop rotation (Kumawat et al., 2022; Layek et al., 2018). The adoption of these practices has, in recent decades, been promoted widely by development non-governmental organizations (NGOs) as a means of achieving the elusive goals of increasing crop yields and food security among impoverished communities, while simultaneously enhancing the environment and its associated ecosystem services (Andersson & D'Souza, 2014; Kassam et al., 2018; Palm et al., 2014). However, the approach remains contentious due to its partial uptake and challenges in adapting the core principles to diverse social–ecological conditions,

especially among resource-constrained smallholders (Baudron et al., 2015; Bouwman et al., 2021; Giller et al., 2009; Ngoma et al., 2021, 2024). With increasing recognition that smallholder farmers may adopt some, but not all, elements of CA depending on their circumstances, attention has focused on the relative importance of each element, not least the role of different variations of intercropping (Ikazaki et al., 2020; Madembo et al., 2020; Mupangwa et al., 2021).

Cereal–legume intercropping, in particular, has received much attention for its multiple agronomic and ecological benefits. It promotes biological nitrogen (N) fixation, improves soil structure, suppresses pests and weeds, and enhances resilience to climate variability (Kumar et al., 2018; Leoni et al., 2022; C. Zhang et al., 2019). Integrating legumes such as soybean (*Glycine max*) into cereal-based systems helps improve soil organic matter, reduce climate-related risks, and support long-term agricultural sustainability (Dave et al., 2024; Abobatta et al., 2021). In maize–soybean (MS) intercropping, for example, soybean contributes to the system by fixing atmospheric nitrogen into a plant-available form that maize can utilize, enhancing soil nitrogen availability for maize (Jing et al., 2025). Additionally, soybean roots releases organic acids which chelate soil minerals, thereby increasing phosphorus (P) solubility in the soil (Bello, 2021). This increase in P availability benefits maize by supporting better root development, which improves its nutrient and water uptake efficiency (Chen et al., 2022).

Despite these benefits, intercropping can also pose challenges due to competition for resources such as light, water, and nutrients, which may reduce the yield of one or both crops (Vernooy, 2022). Studies in Nigeria found that intercropping soybean with maize led to a substantial reduction in soybean yield—by 43.8% in the first year and 55.6% in the second—compared to sole cropping, while maize yield remained largely unaffected (Ijoyah et al., 2013). This was

attributed to maize growing taller and shading the shorter soybean plants (Fan et al., 2018). However, MS intercropping has been shown to improve overall crop productivity and land use efficiency (Xu et al., 2020). Meanwhile, numerous studies have reported that intercropping maize with soybean results in a land equivalent ratio (LER)  $> 1$  (C. Li et al., 2020; Liu et al., 2018). LER is a common metric used to evaluate the productivity of intercropping systems. It compares the total land area required under sole cropping to achieve the same yields as those obtained under intercropping (Dimande et al., 2024). An LER  $> 1$  indicates a yield advantage of intercropping, meaning that the system uses land more efficiently than growing the same crops separately in monoculture (Deb & Dutta, 2022).

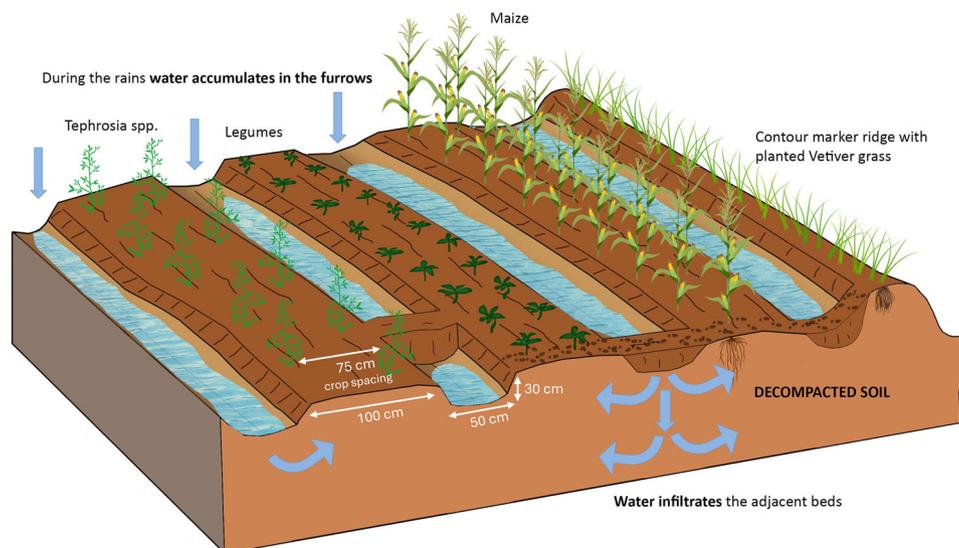
Deep bed farming (DBF), pioneered in Malawi by the NGO Tiyeni, presents a form of regenerative agriculture that aligns with the principles of CA but incorporates some specific adaptations to the environment (Figure 1). Over the last decade it has experienced a rapid and sustained uptake by smallholder farmers throughout northern and central Malawi, driven by its demonstrable impacts on soil health, crop yield increases, water security and wider livelihood benefits (Mvula & Dixon, 2021; A. Phiri et al., 2024). Although DBF incorporates an initial deep tillage phase—setting it apart from CA, which emphasizes minimal soil disturbance even at the outset—it shares several underlying goals and practices with CA. These include improving soil structure, enhancing water infiltration and retention, maintaining soil cover, and promoting sustainable intensification. DBF begins with deep tillage (to a depth of 30 cm) to break up compacted layers and hardpans that are widespread in Malawi and typically restrict root growth (Douglas et al., 1999; Manzeke-Kangara et al., 2024; A. Phiri et al., 2024). This is followed by the construction of permanent raised beds (30 cm high, 1 m wide, 15–25 m long) with adjacent furrows designed to optimize water management—improving infiltration during dry spells and preventing waterlogging during heavy rains (Dixon et al., 2017; Williams et al., 2024). By retaining crop residues as mulch, applying manure, and eliminating conventional tillage (CT) after bed establishment, DBF enhances soil organic matter, improves microbial activity, and increases water retention capacity (Abdallah et al., 2021; Steward et al., 2019). In contrast, traditional cultivation systems in Malawi that include CT are typically characterized by annual ploughing or hoeing, cultivation on narrow ridges, and open furrows that often expose soil to erosion and moisture loss (Sato et al., 2020). Field studies have shown that the structural and biological improvements in DBF create more favorable root zone conditions, with maize roots penetrating 20%–30% deeper under DBF compared to CT (Kahlon & Khurana, 2017; Simwaka et al., 2020). This enhanced root development makes DBF particularly effective in mitigating both drought stress and nutrient deficiencies, even under challeng-

### Core Ideas

- Maize–soybean intercropping delivers significant yield and environmental benefits.
- Deep bed farming consistently outperforms conventional tillage agriculture.
- Maize–soybean intercropping achieves an land equivalent ratio (LER) of 1.21 under deep bed farming.
- Soybean cultivation in plots has residual soil fertility benefits.

ing agronomic conditions such as dry spells (Simwaka et al., 2020). Furthermore, DBF aligns with the principles of CA by reducing soil degradation, enhancing nutrient cycling, and improving water retention and overall soil health (Mvula, 2021). Importantly, DBF is also more flexible and adaptive, designed to be responsive and sensitive to farmers' social–ecological realities—making it more suitable for the diverse, resource-constrained contexts of smallholder farming systems (Mvula & Dixon, 2021).

While evidence continues to demonstrate the agronomic benefits of DBF (Mvula et al., 2025), its performance must be interpreted within the specific social–ecological context in which it is practiced. Northern Malawi represents a distinctive smallholder farming environment within sub-Saharan Africa, characterized by a subhumid to highland agroecology, relatively higher annual rainfall than southern Malawi, and pronounced intra- and inter-seasonal rainfall variability. Agricultural production in this region is dominated by rain-fed, maize-based systems managed by resource-constrained smallholder farmers cultivating small landholdings with limited access to mineral fertilizers and improved seed. The predominant soils are mainly Alisols, which are inherently acidic, structurally fragile, and prone to nutrient leaching and soil organic matter decline under CT practices (Lowole, 1987). These biophysical constraints, together with increasing climate variability and population pressure, have contributed to persistent yield stagnation and declining soil fertility. Northern Malawi is therefore broadly representative of many maize-based smallholder systems across eastern and southern Africa facing similar agroecological and socioeconomic challenges. Within this context, DBF has gained traction as a locally adapted form of CA that emphasizes permanent raised beds, improved water management, residue retention, and reduced soil disturbance following establishment (Mvula & Dixon, 2021). Evaluating MS intercropping within DBF systems under these regional conditions therefore provides important insights into the potential of integrated, climate-resilient intensification strategies for improving crop productivity and soil health in comparable smallholder



**FIGURE 1** Typical layout of deep bed farming.

agroecosystems. While A. Phiri et al. (2024) demonstrated significant advantages of DBF over CT for soil health and crop yields using cereal–legume intercropping systems involving cowpea (*Vigna unguiculata*) and pigeon pea (*Cajanus cajan*), the reported benefits of MS intercropping remain unexplored within the context of DBF. This study therefore aimed to evaluate the effects of integrating MS intercropping with DBF on maize grain yield and soil fertility. We hypothesized that (i) integrating MS intercropping with DBF would enhance maize grain yield and improve soil fertility compared to sole-cropped maize under DBF and all CSs under CT, and (ii) DBF would enhance grain yield and improve soil fertility compared to CT, irrespective of CS.

## 2 | MATERIALS AND METHODS

### 2.1 | Study site description

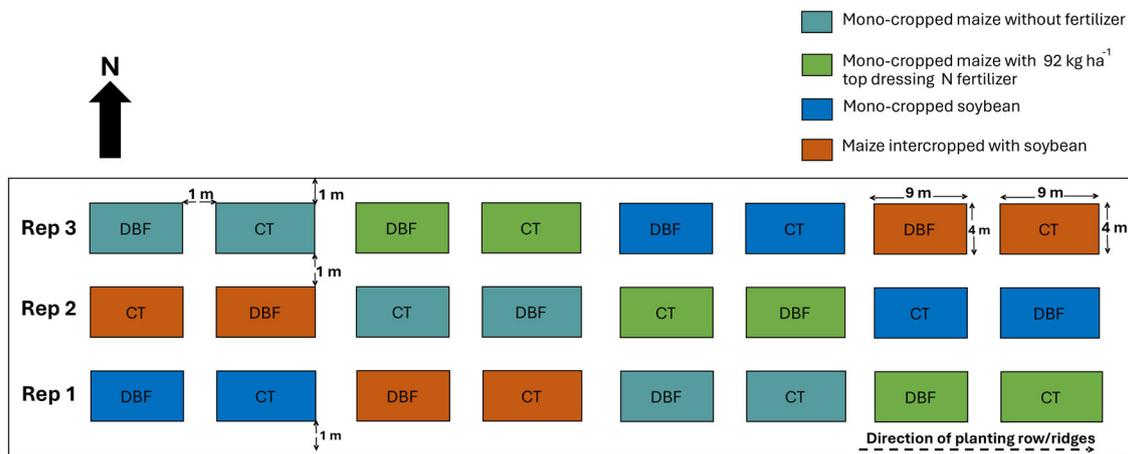
The field experiment was conducted at the Mzuzu Residential Training Center in Malawi, situated at coordinates  $-11^{\circ} 28' N$ ,  $34^{\circ} 02' E$  within the Kavuzi extension planning area. The site receives an average annual rainfall of approximately 1280 mm, with seasonal temperatures fluctuating between  $10^{\circ}C$  in winter and  $32^{\circ}C$  in summer (A. Phiri et al., 2024). The predominant soil type in the area is Alisols (Lowole, 1987). Baseline soil properties, analyzed during the 2022/2023 cropping season from a depth of 0–20 cm, indicated a total nitrogen (N) content of  $1.1 \text{ g kg}^{-1}$ , available phosphorus (P) levels of  $9.33 \text{ mg kg}^{-1}$ , soil organic carbon (SOC) levels of  $12.1 \text{ g kg}^{-1}$ , electrical conductivity of  $11.7 \text{ dS m}^{-1}$ , and pH of 5.43. These pre-experiment soil analyses served as a critical benchmark for assessing the comparative impacts of MS intercropping under two distinct tillage systems (TSs).

### 2.2 | Experimental design and treatment description

The experiment was conducted over three consecutive crop-growing seasons (2022/2023–2024/2025) using a split-plot design. The study initiated during the 2022/2023 growing season with four CSs assigned as main plots: mono-cropped maize without inorganic fertilizer (M), mono-cropped maize with  $92 \text{ kg N ha}^{-1}$  applied (M + 92 N), mono-cropped soybean (S), and intercrop of maize and soybean (MS). Subplot treatments consisted of two TSs: DBF and CT. All treatments were replicated three times (Figure 2).

Each treatment plot measured  $9 \text{ m} \times 4 \text{ m}$ . For mono-cropped maize, row spacing was 75 cm with an intra-row plant spacing of 25 cm. mono-cropped soybean plots had a row spacing of 40 cm and a plant spacing of 30 cm. In the MS intercrop, the distance between maize and soybean rows was 50 cm, with maize intra-row spacing of 25 cm and soybean intra-row spacing of 30 cm. The intercrop followed a 1:2 row arrangement, with one row of maize alternating with two rows of soybeans (Figure 3).

In the first growing season (2022/2023), land preparation, including the formation of deep beds and ridges, was completed in late November prior to planting. Both maize and soybean were sown on December 2, 2022. The seed rate for monocropping was 53,333 and 83,333 plants  $\text{ha}^{-1}$  for maize and soybean, respectively, while intercropping seed rates were 28,571 and 47,691 plants  $\text{ha}^{-1}$ , respectively. Soybean was harvested on March 21, 2023, and maize on April 15, 2023. In the second (2023/2024) and third (2024/2025) growing seasons, all plots were planted with mono-maize to assess the residual effects of the initial treatments. Maize was planted on December 22, 2023 and harvested on April 7, 2024 in the second season, and on December 29, 2024 and harvested on May



**FIGURE 2** Field layout of cropping system and tillage system treatments. Individual plots measured  $8\text{ m} \times 4\text{ m}$  and were separated by  $1\text{ m}$ -wide alleys. The arrow marked “N” indicates north, while the dashed arrow indicates the planting row/ridges direction. CT, conventional tillage; DBF, deep bed farming.



**FIGURE 3** Cropping systems layout, including mono-cropped soybean (a), maize–soybean intercropping (b), and mono-cropped maize (c).

5, 2025 in the third season. Prior to planting in each season, ridges were reconstructed following standard farmer management practices in the study area. Fertilizers were applied on the same day as planting in all seasons, with rates adjusted according to Table 1. Weed management was carried out manually using a hoe, following local smallholder farmer practices. All other agronomic practices recommended for smallholder farmers were observed, and crop residues were returned to the soil after each harvest. The maize variety DK 777 and soybean variety SC Serenade were used in the experiment.

### 2.3 | Plant data collection

Data on maize and soybean yield and yield components were collected across the three growing seasons. For maize, measurements in the first season (2022/2023) included the number of grains per cob, 1000-grain weight (TGW), aboveground total dry biomass, and grain yield, while in the second (2023/2024) and third (2024/2025) seasons, data collection focused on aboveground total dry biomass and grain yield. Physiological maturity was indicated by black layer formation.

For soybean, measurements included the number of pods per plant, 1000-seed weight (TSW), aboveground total dry biomass, and grain yield, with physiological maturity indicated by leaf browning. The number of pods per plant was counted from five sampled plants per plot. For both crops, aboveground total dry biomass included all aboveground components—stems, leaves, and reproductive structures (cobs and husks for maize; pods for soybean)—and was obtained from five plants per plot. Plant materials were oven-dried at  $65^{\circ}\text{C}$  for 72 h until constant weight and measured using a precision digital scale. Harvesting for both crops was carried out within the net plot area ( $7\text{ m} \times 2\text{ m}$ ), leaving a  $1\text{ m}$  guard space on all sides of the  $9\text{ m} \times 4\text{ m}$  gross plot to avoid border effects. Grain yield was calculated based on the harvested area and expressed in  $\text{kg ha}^{-1}$  (Bellaloui et al., 2011) with maize and soybean yields adjusted to 13% moisture content.

### 2.4 | Assessment of productivity: LERs

The productivity of CSs in this study was assessed using the LER. To compute the LER, the yields of the intercropped crops were divided by the net yield of each individual crop

**TABLE 1** Cropping systems, crop types, and fertilizer rates applied across the three growing seasons (2022/2023–2024/2025) at Mzuzu Residential Training Center (RTC).

Growing season	Treatment code	Crop type	Fertilizer rate (kg N ha <sup>-1</sup> )	Cropping system
2022/2023	M	Maize	0	Mono-cropped
	M + 92 N	Maize	92	Mono-cropped
	S	Soybean	0	Mono-cropped
	MS	Maize + soybean	0	Intercropped, 1:2 rows
2023/2024	All plots	Maize	0	Mono-cropped
2024/2025	All plots	Maize	50	Mono-cropped

grown separately and then aggregated. The calculation of the LER for each crop before combining them is known as the partial LER. According to Dhima et al. (2007), the partial LER provides insight into which component crop utilizes resources more efficiently and outcompetes the other. The crop with a greater competitive advantage will have a higher partial LER value. The mathematical equation for calculating both the LER and partial LER is as follows:

$$\text{LER} = \text{LER}_M + \text{LER}_S \quad (1)$$

where

$$\text{LER}_M = Y_{M, \text{intercrop}} / Y_{M, \text{mono-crop}} \quad (2)$$

$$\text{LER}_S = Y_{S, \text{intercrop}} / Y_{S, \text{mono-crop}} \quad (3)$$

Here, *M* and *S* refer to maize and soybean, respectively.  $Y_{M, \text{intercrop}}$  and  $Y_{S, \text{intercrop}}$  represent the grain yields of maize and soybean under intercropping, while  $Y_{M, \text{mono-crop}}$  and  $Y_{S, \text{mono-crop}}$  denote the grain yields under mono-cropping. An LER value of 1.0 indicates that intercropping provides no advantage over mono-cropping; values >1.0 indicate a yield advantage, while values <1.0 suggest that intercropping is disadvantageous.

## 2.5 | Soil sampling and analysis

Soil samples were collected after harvest of maize in the third growing season (2024/2025) at a depth of 0–20 cm in each plot using a soil auger, following a simple random sampling method. The 0- to 20-cm depth was selected because it represents the primary rooting zone of maize and soybean, where the majority of nutrient uptake occurs. Soil from three points within each plot was combined to form composite samples. These samples were analyzed for total nitrogen (N, g kg<sup>-1</sup>), available phosphorus (P, mg kg<sup>-1</sup>), and SOC (g kg<sup>-1</sup>). Analyses were conducted at the Lunyangwa Agricultural Research Station in Mzuzu. Total N was measured using the Kjeldahl digestion method, available P using the Mehlich-3 extrac-

tion method, and SOC using the Walkley–Black method (Anderson & Ingram, 1989).

## 2.6 | Statistical data analysis

All data were analyzed using R software (version 4.4.3). Prior to statistical analysis, response variables were examined for normality and homogeneity of variances using visual inspection of residual plots, the Shapiro–Wilk test for normality, and Levene’s test for homogeneity of variances. When necessary, data were log-transformed to meet model assumptions; however, results are presented using back-transformed means for ease of interpretation. The experiment was analyzed as a split-plot design using analysis of variance (ANOVA). The CS was treated as the main-plot factor, while the TS was treated as the subplot factor. Replication and the replication × CS interaction were included as random effects to account for the split-plot error structure, while CS, TS, and their interaction were treated as fixed effects. Separate analyses were conducted for each growing season. Consequently, year was not included as a factor in the statistical models, and year × treatment interaction effects were not tested. Treatment means were compared using Tukey’s honestly significant difference test at the 5% probability level based on estimated marginal means. The productivity of the MS intercropping system during the first growing season was assessed using the LER and partial LER values. Graphical outputs were generated using the “ggplot2” package, with additional support from the “ggprism,” “ggsci,” and “dplyr” packages.

## 3 | RESULTS

### 3.1 | Crop yield and yield components as influenced by CS and TS during 2022/2023 cropping season

#### 3.1.1 | Maize

The ANOVA revealed a significant interaction ( $p = 0.010$ ) between CS and TS on the number of maize grains per cob

**TABLE 2** The results of analysis of variance for the yield and yield components of maize under different cropping systems and tillage systems during the 2022/2023 growing season.

Cropping systems (CS)	Grains cob <sup>-1</sup>	TGW (g)	Total biomass (kg ha <sup>-1</sup> )	Grain yield (kg ha <sup>-1</sup> )
M	248.9b	254.7c	3480.81ab	2165.98b
M + 92N	394.8a	409.0a	4818.70a	3786.96a
MS	412.2a	353.7b	2645.56b	1800.98b
<i>F</i> pr. (CS)	<0.001	<0.001	0.029	0.002
LSD <sub>0.05</sub> (CS)	34.17	36.76	1381	602.5
Tillage systems (TSs)				
DBF	372.0a	354.1a	4045.71a	2948.53a
CT	332.9b	324.2b	3251.01b	2220.75b
<i>F</i> pr. (TS)	<0.001	0.037	0.005	0.007
LSD <sub>0.05</sub> (TS)	14.00	27.30	448.3	440.8
<i>F</i> pr. (CS × TS)	0.010	0.675	0.246	0.921
CV (%)	3.4	7.0	10.7	14.8

Note: Means with different letters within each column are significantly different.

Abbreviations: M, mono-cropped maize without inorganic fertilizer; M + 92 N, mono-cropped maize and supplied with 92 kg N ha<sup>-1</sup>; MS, maize–soybean intercropping; *F* pr., *F* probability; LSD<sub>0.05</sub>, least significant difference at 5% significant level; CV (%), coefficient of variation; DBF, deep bed farming; CT, conventional tillage; TGW, 1000-grain weight.

(Table 2). The MS:DBF treatment produced the highest number of grains per cob, recording 96.6% more grains than the lowest performing treatment, M:CT (Figure 4). Higher grain numbers were also observed in MS:CT and M + 92 N:DBF, which were statistically at par with each other and showed increases of 92.2% and 93.6%, respectively, compared with M:CT; however, both still remained lower than MS:DBF. Although no significant differences were detected among MS:DBF, MS:CT, and M + 92 N:DBF, MS:DBF numerically outperformed MS:CT by 2.3% and M + 92 N:DBF by 1.6%. The M + 92 N:CT treatment produced significantly fewer grains per cob than MS:DB, MS:CT, and M + 92 N:DB, but still exceeded M:DB and M:CT by 78.8% and 37.6%, respectively. Overall, M:CT recorded the lowest number of grains per cob across all treatments.

The results indicated no significant interaction ( $p = 0.675$ ) between CS and TS on maize TGW (Table 2). However, both CS and TS had significant main effects on TGW ( $p < 0.001$  and  $p = 0.037$ , respectively). Across TS, mono-cropped M + 92 N produced a TGW that was 15.6% higher than MS intercropping and 60.6% higher than mono-cropped M, while MS intercropping produced a TGW that was 38.9% higher than mono-cropped M. Across CS, maize grown under DBF increased TGW by 9.2% compared to CT.

Similarly, no significant interaction ( $p = 0.246$ ) between CS and TS was observed for maize aboveground total biomass (Table 2). Both CS and TS had significant main effects ( $p = 0.029$  and  $p = 0.005$ , respectively). Across TS, mono-cropped M + 92 N produced 38.4% higher aboveground biomass than mono-cropped M and 82.1% higher biomass than MS intercropping, while mono-cropped M produced

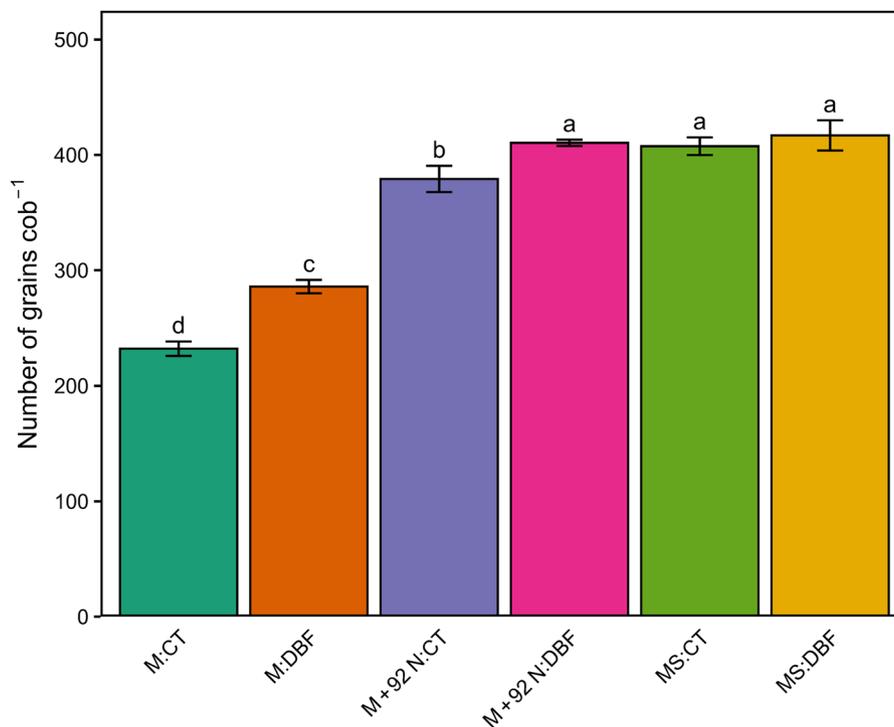
38.4% higher biomass than MS intercropping. Across CS, maize grown under DBF increased aboveground total biomass by 24.4% compared to CT.

Maize grain yield followed a similar pattern (Table 2). No significant interaction ( $p = 0.921$ ) between CS and TS was detected, but both CS and TS significantly affected grain yield ( $p = 0.002$  and  $p = 0.007$ , respectively). Across TS, mono-cropped M + 92 N produced a grain yield that was 74.8% higher than mono-cropped M and 110.3% higher than MS intercropping, while mono-cropped M produced a grain yield that was 20.3% higher than MS intercropping. Across CS, maize grown under DBF increased grain yield by 32.8% compared to CT.

### 3.1.2 | Soybean

ANOVA showed no significant interaction ( $p = 0.780$ ) between CS and TS on the number of soybean pods per plant (Table 3). However, both CS and TS had significant main effects ( $p = 0.016$  and  $p = 0.032$ , respectively). Across TS, mono-cropped S produced a higher number of pods per plant than MS intercropping, with an increase of 21.7%. Across CS, soybean grown under DBF produced 15.5% more pods per plant than under CT.

No significant interaction ( $p = 0.429$ ) between CS and TS was observed for soybean TSW (Table 3). The CS had a significant ( $p = 0.041$ ) main effect on TSW, whereas the effect of TS was not significant ( $p = 0.084$ ). Across TS, mono-cropped S produced a 14.6% higher TSW than soybean grown in MS intercropping. Although TS had no significant effect,



**FIGURE 4** Interaction effects of cropping systems and tillage systems on number of grains per cob. Different letters indicate significant differences among treatments based on Tukey's honestly significant difference (HSD) test at  $p < 0.05$ . M:CT, mono-cropped maize under conventional tillage; M:DBF, mono-cropped maize under deep bed farming; M + 92 N:CT, mono-cropped maize supplied with 92 kg N ha<sup>-1</sup> under conventional tillage; M + 92 N:DBF, mono-cropped maize supplied with 92 kg N ha<sup>-1</sup> under deep bed farming; MS:CT, maize–soybean intercropping under conventional tillage; MS:DBF, maize–soybean intercropping under deep bed farming.

**TABLE 3** The results of analysis of variance for the yield and yield components of soybean under different cropping systems and tillage systems during the 2022/2023 growing season.

Cropping systems (CS)	Pods plant <sup>-1</sup>	TSW (g)	Total biomass (kg ha <sup>-1</sup> )	Grain yield (kg ha <sup>-1</sup> )
S	52.8a	189.5a	2932.29a	1743.94a
MS	43.4b	163.6b	1659.18b	975.44b
<i>F</i> pr. (CS)	0.016	0.041	0.018	0.021
LSD <sub>0.05</sub> (CS)	5.24	23.29	744.6	488.8
<b>Tillage systems (TSs)</b>				
DBF	51.5a	180.7a	2413.33a	1436.94a
CT	44.6b	172.5a	2178.14b	1282.44b
<i>F</i> pr. (TS)	0.032	0.084	0.046	0.037
LSD <sub>0.05</sub> (TS)	5.92	9.99	227.9	138.9
<i>F</i> pr. (CS × TS)	0.780	0.429	0.370	0.248
CV (%)	7.7	3.5	6.2	6.4

Note: Means with different letters within each column are significantly different.

Abbreviations: S, mono-cropped soybean; MS, maize–soybean intercropping; *F* pr., *F* probability; LSD<sub>0.05</sub>, least significant difference at 5% significant level; CV (%), coefficient of variation; DBF, deep bed farming; CT, conventional tillage; TSW, 1000-seed weight.

soybean grown under DBF showed numerically higher TSW than under CT, with a mean increase of 4.8%.

Similarly, no significant interaction ( $p = 0.370$ ) between CS and soybean aboveground biomass was detected (Table 3).

Both CS and TS exerted significant main effects ( $p = 0.018$  and  $p = 0.041$ , respectively). Across TS, mono-cropped S produced 76.7% greater biomass than soybean grown in MS intercropping. Across CS, soybean grown under

**TABLE 4** Productivity from yield and yield component data of sole and intercropping system.

Cropping systems (CS)	Variable	Partial value of LERs		
		Maize	Soybean	LER
MS	Grain yield	0.59	0.57	1.16
<b>Tillage systems (TSs)</b>				
DBF	Grain yield	0.62	0.59	1.21
CT	Grain yield	0.56	0.53	1.09

Note: The LERs and partial LERs are shown as mean values of indices, making them unit-less. An LER value >1 indicates that intercropping was advantageous. Abbreviations: CT, conventional tillage; DBF, deep bed farming; LER, land equivalent ratio; MS, maize–soybean intercropping.

DBF increased biomass by 10.8% compared to those under CT.

Soybean grain yield followed a comparable trend (Table 3). No significant interaction ( $p = 0.248$ ) between CS and TS was observed, while both CS and TS had significant main effects ( $p = 0.021$  and  $p = 0.037$ , respectively). Across TS, mono-cropped S produced 78.8% higher grain yield than soybean grown in MS intercropping. Across CS, soybean grown under DBF increased grain yield by 12% compared to those under CT.

### 3.2 | Productivity and land use efficiency of MS intercropping

The results indicated that MS intercropping provided a yield advantage of 16% (LER = 1.16) (Table 4). The DBF had an effect on MS intercropping, as practicing MS intercropping further increased yield advantage by 21% (LER = 1.21) compared to when MS was intercropped on CT (LER = 1.09). The partial LERs further highlighted that maize was more competitive than soybean in utilizing resources such as light, water, and nutrients under both DBF and CT.

### 3.3 | Residue effects of CS and TS on maize productivity and soil fertility (2023/2024–2024/2025)

#### 3.3.1 | Maize biomass and grain yield

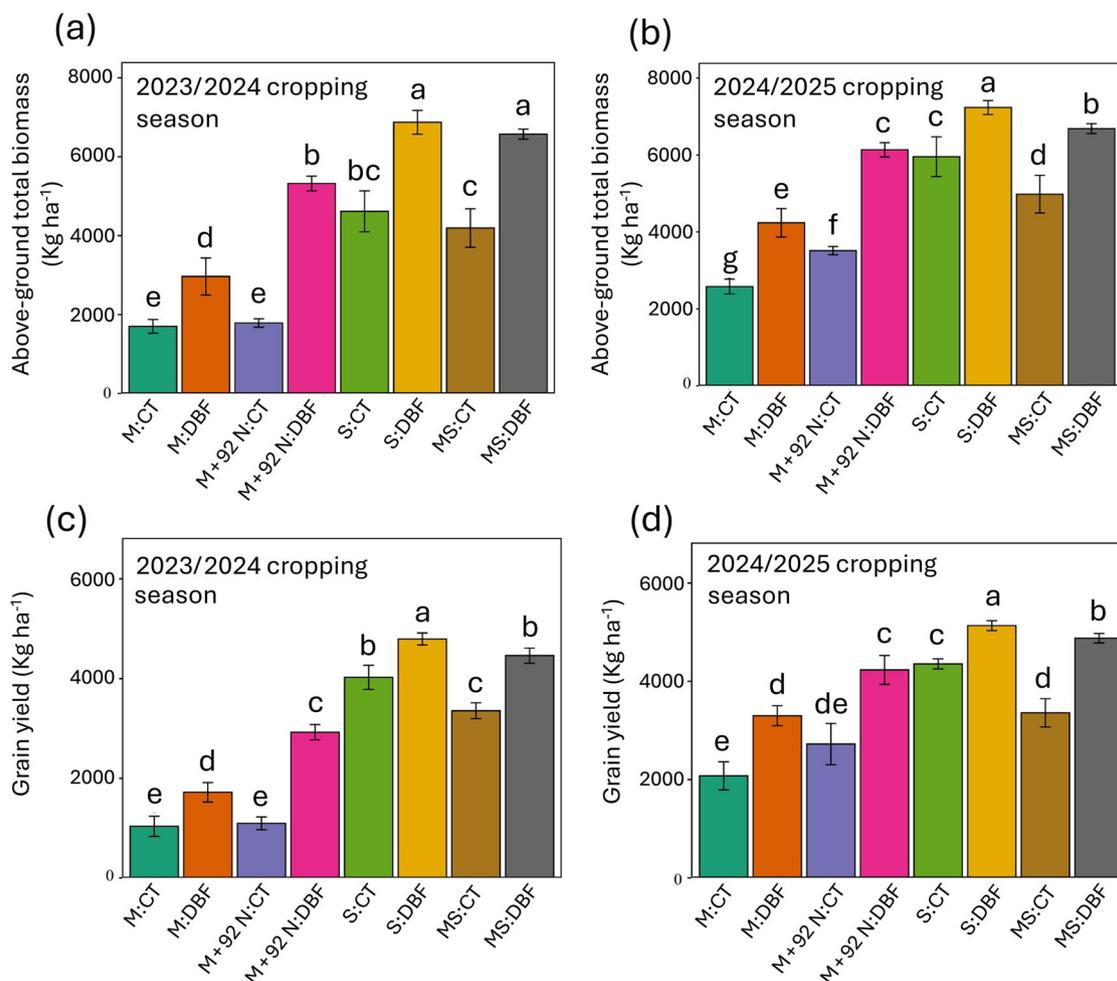
Significant interactions between CS and TS were observed for maize aboveground total biomass in both the 2023/2024 and 2024/2025 cropping seasons ( $p = 0.038$  and  $p < 0.001$ , respectively) (Figure 5a). In the 2023/2024 season, the highest aboveground biomass was recorded under S:DBF (7570.8 kg ha<sup>-1</sup>), which represented a 345.2% increase compared with M:CT (1700.7 kg ha<sup>-1</sup>). Similarly high biomass was observed under MS:DBF (6671.1 kg ha<sup>-1</sup>), which was at par with S:DBF and produced 292.3% more biomass than M:CT. The M + 92 N:DBF produced lower biomass than S:DBF and MS:DBF but still exceeded M:CT by 212.9%. Intermediate

biomass values were observed under S:CT and MS:CT, which produced 171.4% and 146.5% higher biomass than M:CT, respectively. The M:DBF treatment produced 74.4% more biomass than M:CT, whereas the lowest biomass values were recorded under M + 92 N:CT and M:CT, with M + 92 N:CT slightly outperforming M:CT by 4.8%.

A similar trend was observed in the 2024/2025 season, with the highest maize biomass again recorded under S:DBF (7633.2 kg ha<sup>-1</sup>), representing a 208.0% increase compared with M:CT (2478.5 kg ha<sup>-1</sup>). Biomass under MS:DBF was at par with S:DBF and exceeded M:CT by 181.8%. The M + 92 N:DBF and S:CT treatments produced 140.3% and 147.5% higher biomass than M:CT, respectively. The MS:CT treatment produced intermediate biomass (100.9% higher than M:CT), while M:DBF and M + 92 N:CT recorded lower biomass than the above treatments but still produced 70.9% and 41.7% higher biomass, respectively, than M:CT.

Maize grain yield also exhibited a significant interaction between CS and TS in both the 2023/2024 and 2024/2025 cropping seasons ( $p = 0.011$  and  $p = 0.001$ , respectively) (Figure 5b). In the 2023/2024 season, the highest grain yield was recorded under S:DBF (4794.7 kg ha<sup>-1</sup>), which represented a 363.3% increase compared with M:CT (1034.9 kg ha<sup>-1</sup>). Grain yield under MS:DBF was at par with S:CT; both treatments produced lower yields than S:DBF but exceeded M:CT by 331.1% and 289.0%, respectively. Intermediate grain yields were observed under M + 92 N:DBF and MS:CT, which produced 221.2%–224.2% higher grain yields than M:CT, with MS:CT slightly exceeding M + 92 N:DBF. The M:DBF treatment produced a 66.0% higher grain yield than M:CT but remained lower than the other treatments. The lowest grain yields were recorded under M + 92 N:CT and M:CT, with M + 92 N:CT slightly outperforming M:CT by 2.9%.

A similar pattern was observed in the 2024/2025 season, with the highest grain yield again recorded under S:DBF (4736.7 kg ha<sup>-1</sup>), representing a 176.2% increase compared with M:CT (1715.2 kg ha<sup>-1</sup>). High grain yields were also observed under MS:DBF (4500.1 kg ha<sup>-1</sup>), which exceeded M:CT by 162.4% but remained lower than S:DBF. The S:CT and M + 92 N:DBF treatments produced 128%–134% higher grain yields than M:CT, with S:CT slightly exceeding M + 92 N:DBF. The MS:CT treatment produced intermediate



**FIGURE 5** Interaction effects of cropping systems and tillage systems on aboveground total biomass for (a) 2023/2024 and (b) 2024/2025, and grain yield for (c) 2023/2024 and (d) 2024/2025. Different letters indicate significant differences among treatments based on Tukey's honestly significant difference (HSD) test at  $p < 0.05$ . M:CT, mono-cropped maize under conventional tillage; M:DBF, mono-cropped maize under deep bed farming; M + 92 N:CT, mono-cropped maize supplied with 92 kg N ha<sup>-1</sup> under conventional tillage; M + 92 N:DBF, mono-cropped maize supplied with 92 kg N ha<sup>-1</sup> under deep bed farming; MS:CT, maize–soybean intercropping under conventional tillage; MS:DBF, maize–soybean intercropping under deep bed farming.

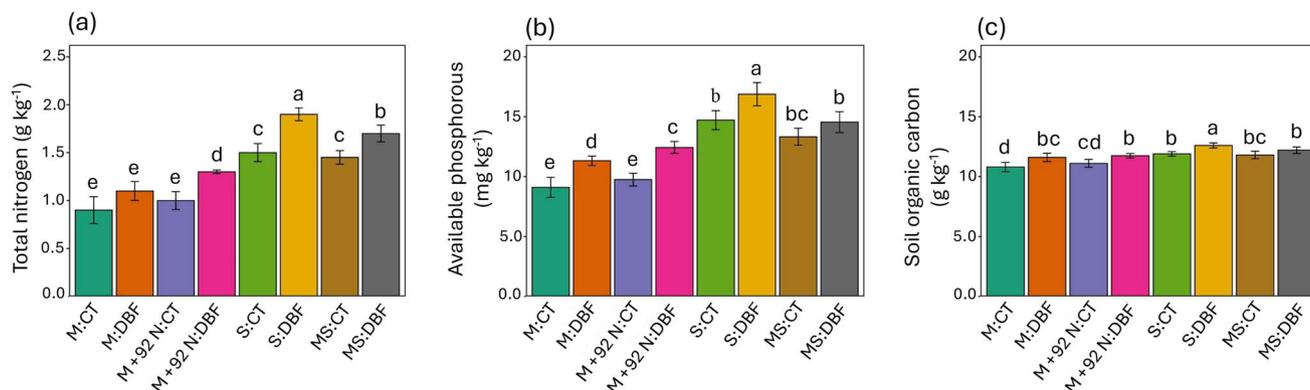
grain yields, exceeding those of M:DBF, M + 92 N:CT, and M:CT by 5.3%, 10.3%, and 80.8%, respectively. The M:DBF treatment yielded more grain than M + 92 N:CT and M:CT but less than the higher yielding treatments, while M:CT recorded the lowest maize grain yield across all treatments.

### 3.3.2 | Soil chemical properties

ANOVA revealed a significant interaction ( $p = 0.027$ ) between CS and TS on soil total N (Figure 6a). The highest total N was recorded under S:DBF (1.72 g kg<sup>-1</sup>), representing a 97.7% increase compared with the lowest value observed under M:CT (0.87 g kg<sup>-1</sup>). High total N was also observed under MS:DBF (1.59 g kg<sup>-1</sup>), which exceeded M:CT by 82.8% but remained lower than S:DBF. The S:CT and MS:CT treatments were at par with each other and pro-

duced 62.1%–65.4% higher total N than M:CT, with S:CT slightly exceeding MS:CT. Among treatments with lower total N, M:DBF showed a 37.9% increase compared with M:CT, whereas M + 92 N:CT produced total N values at par with M:CT, despite a small numerical increase of 2.7%.

The results also showed a significant interaction ( $p = 0.019$ ) between CS and TS on available P (Figure 6b). The highest available P was observed under S:DBF (16.1 mg kg<sup>-1</sup>), representing a 78.9% increase compared with M:CT (9.0 mg kg<sup>-1</sup>), which recorded the lowest value. Higher available P levels were also recorded under S:CT (14.8 mg kg<sup>-1</sup>) and MS:DBF (14.6 mg kg<sup>-1</sup>), which were at par with each other, corresponding to 64.4% and 62.2% higher values than M:CT, respectively, but remained lower than S:DBF. The MS:CT treatment produced intermediate available P, showing a 46.7% increase compared with M:CT and overlapping with S:CT, MS:DBF, and M + 92 N:DBF, indicating no clear separa-



**FIGURE 6** Total nitrogen (a), available phosphorus (b) and soils organic carbon (c) as influenced by different cropping systems and tillage systems. Different letters indicate significant differences among treatments based on Tukey's honestly significant difference (HSD) test at  $p < 0.05$ . M:CT, mono-cropped maize under conventional tillage; M:DBF, mono-cropped maize under deep bed farming; M + 92 N:CT, mono-cropped maize supplied with 92 kg N ha<sup>-1</sup> under conventional tillage; M + 92 N:DBF, mono-cropped maize supplied with 92 kg N ha<sup>-1</sup> under deep bed farming; MS:CT, maize–soybean intercropping under conventional tillage; MS:DBF, maize–soybean intercropping under deep bed farming.

tion among these treatments. The M:DBF treatment produced lower available P than S:CT, MS:DBF, and M + 92 N:DBF but still showed a 24.4% increase compared with M:CT. In contrast, M + 92 N:CT was at par with M:CT, despite a small numerical increase of 8.9%.

A significant interaction ( $p = 0.041$ ) between CS and TS was also observed for SOC (Figure 6c). The highest SOC was recorded under S:DBF (12.5 g kg<sup>-1</sup>), representing a 15.7% increase compared with M:CT (10.8 g kg<sup>-1</sup>), which recorded the lowest SOC. Higher SOC levels were also observed under MS:DBF (12.2 g kg<sup>-1</sup>), S:CT (11.9 g kg<sup>-1</sup>), and M + 92 N:DBF (11.7 g kg<sup>-1</sup>), which were at par with each other, corresponding to increases of 13.0%, 10.2%, and 9.3%, respectively, compared with M:CT, but remaining lower than S:DBF. Intermediate SOC values were recorded under M:DBF and MS:CT, showing increases of 8.3% and 7.4%, respectively, compared with M:CT. SOC values under these treatments overlapped with those of MS:DBF, S:CT, and M + 92 N:DBF, as well as with M + 92 N:CT, with M:DBF slightly exceeding MS:CT. The M + 92 N:CT treatment resulted in SOC values that were at par with M:CT; however, it slightly outperformed M:CT by 2.8%.

## 4 | DISCUSSION

### 4.1 | Effects of CS and TS on crop yield and yield components (2022/2023)

During the first growing season, maize grown in MS intercropping exhibited superior yield components compared with mono-cropped M, a response largely attributable to the nitrogen contribution of soybean (Feng et al., 2021). As a legume, soybean fixes atmospheric nitrogen through symbiosis with rhizobia bacteria (Mujtaba et al., 2024), enriching the rhizosphere with plant-available nitrogen that can be utilized

by the associated maize crop. This facilitative interaction enhances maize growth and reproductive development, leading to improvements in yield components (Sachan et al., 2023). Similar benefits of MS intercropping on maize yield components have been widely reported, including increases in leaf area development and kernel formation relative to monoculture maize (Liu et al., 2023; Xiaona et al., 2019). However, the lower total aboveground biomass and grain yield in MS intercropping compared to mono-cropped M can be attributed to the reduced maize plant density required to accommodate soybean, which limits dry matter accumulation and final yield per unit area (Huang et al., 2019; D. Zhang et al., 2020).

Regarding TS, maize yield and yield components were higher under DBF compared to CT. This benefit is likely linked to the principles of CA applied in DBF, particularly residue retention into the soil during the formation of permanent raised beds. These practices help conserve moisture, improve nutrient availability, and enhance soil fertility (Biswakarma et al., 2021; Habig et al., 2015), creating favorable conditions for maize growth (Qiao et al., 2022). According to Tiyeni (2021) and Mvula (2021), farmers using DBF often report substantial improvements in soil health and crop performance, with many achieving more than double the maize yields compared to CT. Similarly, A. Phiri et al. (2024) reported consistently higher maize yields under DBF, highlighting its agronomic potential.

On the other hand, soybean yield and yield components were lower in MS than in mono-cropped S, primarily due to shading effects caused by the taller maize plants (Mugi-Ngenga et al., 2022). The maize canopy restricts light interception by soybean, reducing photosynthetic activity and impairing key growth processes such as pod formation and grain filling (Harouna et al., 2020). This light limitation creates a suboptimal microenvironment that is further intensified by interspecific competition for space and soil nutrients, collectively suppressing soybean growth and yield (Wei et al.,

2022). These findings are supported by previous studies such as Wu et al. (2023), who reported that taller crops in intercropping systems restrict resource access for shorter companion crops, while Anyoni et al. (2023) and A. T. Phiri et al. (2025) documented consistent yield reductions in soybean due to intensified interspecific competition.

Regarding TS, soybean grown under DBF produced higher yields and yield components than under CT, likely due to the enhanced soil conditions promoted by CA practices. The incorporation of crop residues during bed formation enhances microbial activity, accelerating organic matter decomposition and nutrient cycling (Khan et al., 2024; Y. Li et al., 2025). This process increases soil nitrogen content and its availability in plant-accessible forms such as ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ) (Yang et al., 2025). Nitrogen in these forms is preferentially allocated to developing organs such as young leaves and pods, paralleling the distribution seen with nitrogen fixed in root nodules (Lilay et al., 2024). Moreover, residue retention reduces nitrogen leaching and improves both nutrient use efficiency and soil moisture retention (Jayaraman et al., 2021; Page et al., 2020). In contrast, CT systems provide less available nitrogen due to inadequate residue management (Topa et al., 2021). Supporting evidence shows higher nitrate levels in cover crop plots managed under CA compared to CT (Yadav et al., 2021).

## 4.2 | Productivity and land-use efficiency of MS intercropping

Intercropping maize and soybean demonstrated higher overall productivity from the same land area, as reflected by the LER, compared to their respective sole crops. An LER > 1.0 for MS intercropping has been consistently documented in previous studies (Unay et al., 2021; Wei et al., 2022). Bayeh et al. (2022) explained that an LER > 1.0 signifies an advantage in land use efficiency, indicating that intercropping produces a higher combined yield per unit area than cultivating the crops separately in monoculture systems. The higher partial LERs observed for maize suggest that maize is more competitive than soybean in the intercrop, benefiting from the nitrogen fixed by soybean to enhance its growth, development, and yield (M. Li et al., 2023). This advantage is likely attributed to maize's greater height, which allows it to overshadow soybean, capturing more sunlight and utilizing other resources more effectively (S. Li et al., 2021).

## 4.3 | Residual effects of CS and TS on maize productivity and soil fertility

The higher maize biomass and grain yield in the 2023/2024 and 2024/2025 seasons from plots previously cultivated with

mono-cropped soybean under deep bed farming (S:DBF), followed by MS:DBF, can be attributed to the combined residual benefits of the leguminous crop and the DBF practice. Soybean residues decompose more rapidly than cereal residues due to their relatively low carbon-to-nitrogen (C:N) ratio, high N concentration, and lower lignin and polyphenol contents, which promote microbial activity and accelerate residue breakdown and nutrient mineralization. As a result, soybean residues release key nutrients—especially N, P, and potassium (K)—into the soil within a relatively short period (Hunag et al., 2024). This fast decomposition is beneficial because it synchronizes nutrient release with the demands of subsequent crops (Sadra et al., 2023). For example, studies in the US Coastal Plain found that cover crops like soybean provided up to 82 kg of nitrogen, 15 kg of phosphorus, and 89 kg of potassium per hectare in 2019, leading to higher corn yields when terminated 4 weeks before corn planting (Poudel et al., 2023). Similarly, in African farming systems, herbaceous and woody legumes typically fix between 40 and 70 kg N ha<sup>-1</sup> per season, with legume residues providing additional residual nitrogen that benefits subsequent cereal crops such as maize (A. T. Phiri & Njira, 2023; Sanginga, 2003). In addition, DBF enhances soil structure, facilitating root development and access to nutrients and water from deeper layers (Williams et al., 2024). It also improves soil moisture retention by minimizing losses through percolation and evaporation, thus enhancing water use efficiency—a key advantage for moisture-sensitive crops like maize (Anyoni et al., 2023; Munmun et al., 2024). In contrast, the lower maize yield and yield components observed in plots previously planted with mono-cropped M under CT (M:CT) in the first season can be attributed to the slow decomposition and limited nutrient release from cereal residues, which is further constrained under CT practice (Gorooui et al., 2023). Unlike legume residues, maize residues have a higher C:N ratio and lower nitrogen content, resulting in slower decomposition and less efficient nutrient cycling (Du et al., 2024).

The observed increases in total N, available P, and SOC in legume-based CSs under DBF can be attributed to the decomposition of leguminous crops like soybean and the integration of CA principles into DBF. These effects reflect the cumulative impact of three consecutive cropping seasons following the application of treatments in the first season. Soybean enriches the soil with nitrogen through atmospheric N fixation, thereby increasing total N levels (Brambilla et al., 2022). Additionally, its roots release organic acids such as citric and malic acids, which chelate soil minerals like aluminum (Al) and iron (Fe), improving phosphorus solubility (Panchal et al., 2021). These exudates also stimulate phosphate-solubilizing microorganisms, enhancing overall nutrient availability (Ansari et al., 2023). The low C:N ratio of legume residues accelerates organic matter decomposition, contributing to higher SOC accumulation (Thompson

et al., 2024). Practices such as crop residue retention and minimal soil disturbance in DBF further support microbial activity, which plays a vital role in nutrient cycling and SOC buildup (Q. Li et al., 2022). The observed interaction between CS and TS suggests that the combined effect of legumes and DBF has a greater influence on soil chemical properties than either factor alone. Although MS intercropping recorded lower N, P, and SOC levels than mono-cropped S, it still outperformed mono-cropped M under both DBF and CT. This may be due to improved nitrogen availability from soybean, which stimulates microbial breakdown of maize residues and reduces nutrient immobilization (Hall et al., 2019). However, the lower nutrient levels in MS compared to Mono-cropped S may also reflect nutrient immobilization caused by cereal crop residues, which can constrain soybean's contribution to soil fertility (Raza et al., 2019).

#### 4.4 | Relevance to smallholder farming systems and adoption considerations

The findings of this study are highly relevant to smallholder farming systems in northern Malawi and across much of eastern and southern Africa, where maize-based production dominates and access to mineral fertilizers remains limited. The observed yield advantages and soil fertility improvements under legume-based systems are consistent with regional evidence demonstrating the benefits of cereal–legume integration under conservation-oriented management (Mupangwa et al., 2021). Similar studies in Malawi, Zambia, and Zimbabwe have reported increased maize productivity and improved nitrogen availability following soybean, cowpea, or pigeon pea integration, particularly under reduced tillage or residue-retentive systems (Muoni et al., 2024; Ngongoni et al., 2007; Vwalika et al., 2024).

Importantly, the DBF system evaluated in this study was specifically designed to align with smallholder constraints, relying on manual labor, permanent bed structures, and minimal external inputs after establishment. The strong residual benefits observed following soybean cultivation suggest that smallholder farmers with limited fertilizer access can achieve meaningful yield gains through biologically driven nutrient inputs. Moreover, the enhanced land-use efficiency ( $LER > 1$ ) indicates that intercropping offers a viable strategy for maximizing productivity on small landholdings, a key consideration in densely populated rural areas.

Nevertheless, several practical barriers may constrain widespread adoption. Establishing deep beds requires substantial initial labor investment, which may limit uptake among labor-constrained households, particularly female-headed or elderly households (Mvula, 2021). Access to quality soybean seed, knowledge of appropriate intercropping arrangements, and short-term yield trade-offs—especially

reduced soybean yield under intercropping—may also discourage adoption. Additionally, competing uses for crop residues, such as livestock feed, can reduce residue retention and compromise soil health benefits (Mvula & Dixon, 2021).

Addressing these constraints will require integrated extension approaches that combine farmer training, access to legume seed, labor-saving innovations, and participatory adaptation of DBF practices to local contexts. When supported through appropriate institutional and extension frameworks, MS intercropping under DBF represents a realistic, scalable pathway toward climate-resilient intensification for smallholder farmers in Malawi and similar agroecological zones.

#### 4.5 | Study limitations and implications for field application

While the results of this study demonstrate clear agronomic and soil fertility benefits of integrating MS intercropping with DBF, several limitations should be acknowledged. First, the experiment was conducted over three consecutive cropping seasons, which, although sufficient to capture short- to medium-term residual effects, may not fully reflect longer term SOC dynamics and nutrient stabilization processes. Changes in soil chemical properties, particularly SOC, often require longer time horizons to reach equilibrium, and thus the magnitude of long-term benefits under sustained DBF management may be underestimated in this study.

Second, the experimental design involved changes in cropping and fertilizer treatments after the first season, with all plots planted to mono-maize in the second and third seasons to assess residual effects. While this approach is appropriate for evaluating legacy effects of legumes and TSs, it limits direct year-to-year comparisons of CS performance and precludes formal testing of year  $\times$  treatment interactions. Consequently, observed differences in later seasons should be interpreted as cumulative residual responses rather than continuous treatment effects.

Third, the trial was conducted under controlled research conditions with consistent plot management and careful residue retention, which may not fully represent the heterogeneity of management practices on farmers' fields. In practice, variability in residue availability, labor constraints, and farmer compliance with recommended bed maintenance could influence the magnitude of benefits observed. Nonetheless, the relative performance trends between DBF and CT, and between legume-based and cereal-only systems, are likely robust, as they align with both farmer-reported outcomes and independent field studies conducted in similar environments (Mvula & Dixon, 2021; A. Phiri et al., 2024; Tiyeni, 2021).

Despite these limitations, the study provides realistic and field-relevant insights because treatments and management

practices closely reflected smallholder farmer conditions, including manual land preparation, rainfed production, and limited fertilizer inputs. The results therefore offer a credible basis for guiding on-farm adaptation and scaling of MS intercropping within DBF systems, while highlighting the need for longer term studies to capture sustained soil health and productivity outcomes.

## 5 | CONCLUSION

This study demonstrates the transformative potential of MS intercropping combined with DBF to enhance crop productivity and soil fertility in maize-based systems in Malawi. Integrating soybean into maize systems improved yield components through biological nitrogen fixation, while intercropping achieved greater land-use efficiency than monocropping, as indicated by LER values exceeding 1. The higher LER observed under DBF (1.21) compared with CT (1.09) highlights the added benefit of conservation-oriented soil management in strengthening intercropping performance. The DBF system, through minimal soil disturbance, soil fertility restoration, and improved water conservation, consistently resulted in higher nutrient availability, increased SOC, and enhanced crop productivity, demonstrating its potential to support sustainable intensification in smallholder farming systems. Furthermore, the combined application of intercropping and DBF aligns with CA principles, reinforcing their relevance for climate-smart agricultural development.

Adoption of MS intercropping under DBF offers a practical strategy for smallholder farmers to improve food production per unit land while enhancing soil health and reducing environmental degradation. The effectiveness of this integrated system, however, depends on its adaptation to local agroecological conditions and management practices. Future research should focus on optimizing intercropping configurations, evaluating alternative legume species, and assessing the scalability of DBF across diverse farming contexts to facilitate broader adoption. This study offers critical insights into the development of sustainable and climate-resilient farming systems, paving the way for a more productive, ecologically sound, and food-secure future.

## AUTHOR CONTRIBUTIONS

**Godfrey Kumwenda:** Data curation; formal analysis; funding acquisition; investigation; methodology; project administration; writing—original draft. **Augustine Talababie Phiri:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Zondo Chibambo:** Formal analysis; supervision; writing—review and editing. **Francina Lerato Kuwali:** Data curation; writing—original draft. **Pemphero Kashoni:** Data curation;

writing—original draft. **Alan Dixon:** Writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

Godfrey Kumwenda is employed by Tiyeni as a training manager. Alan Dixon serves as a trustee of Tiyeni. The remaining authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data are available from the authors upon reasonable request.

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