Participatory assessment of maize productivity following the transition from conventional ridge tillage to deep bed farming system in Malawi

Emmanuel Junior Zuza[1,2*], Yoseph Araya[2], William Banda[3], Albert Mvula[4], France M.T. Gondwe[5], Rupert Douglas-Bate[6], Linda Muzangwa[1]

[1]School of Agricultural Sciences and Practice, The Royal Agricultural University, GL7 6JS, Cirencester, UK,
[2]School of Environment, Earth and Ecosystem Sciences, The Open University, MK7 6AA, Milton Keynes, UK,
[3]Centre for Agricultural Data Science, Harper Adams University, TF10 8NB, Newport, UK,
[4]Countryside and Community Research Institute, University of Gloucestershire, GL50 4AZ, Cheltenham, UK,
[5]Tiyeni, Mzuzu, Malawi, [6]Global MapAid, Alwyn Lawn House, HP17 8RZ, Aylesbury, UK.

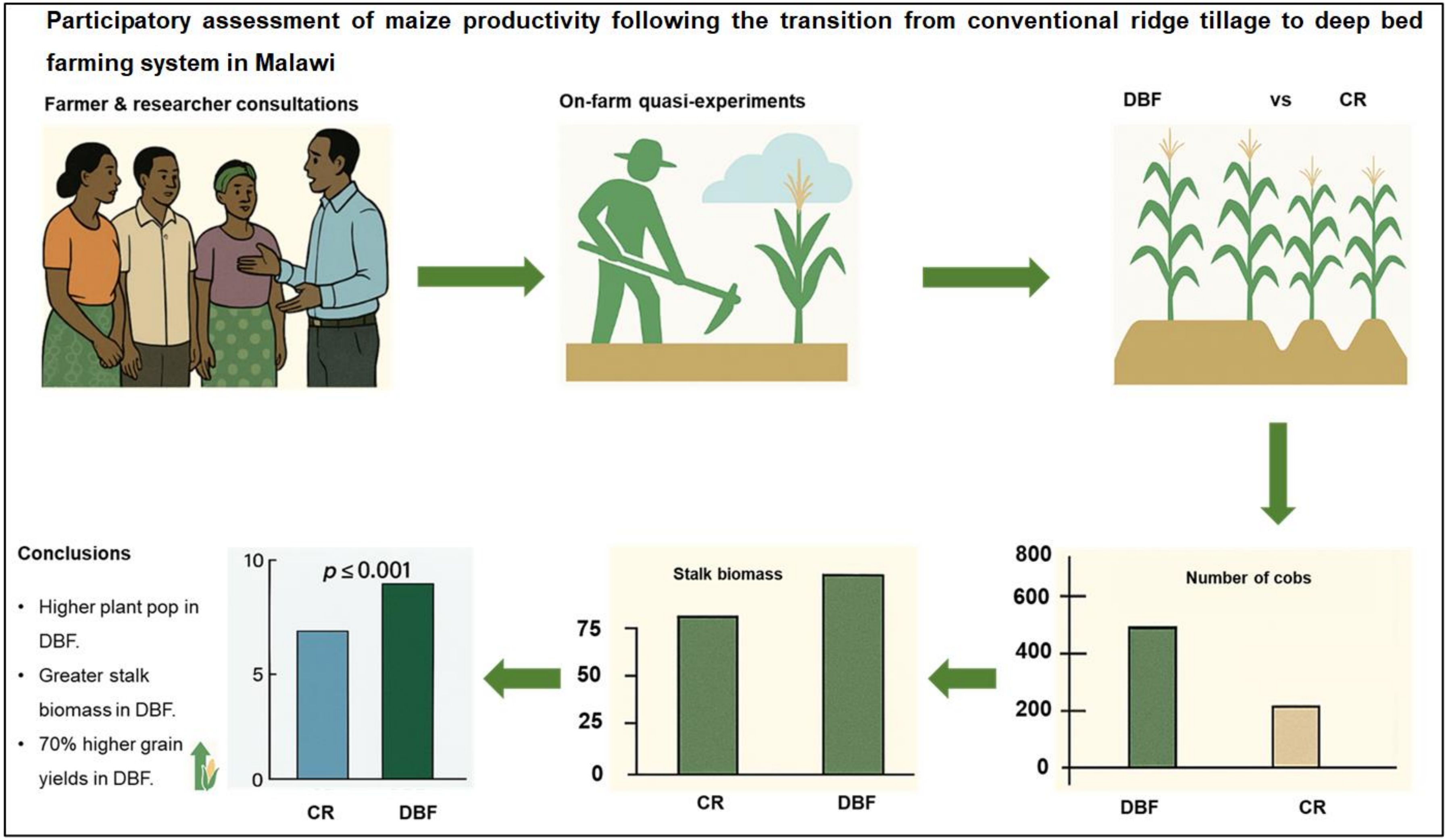
[*]Emmanuel.Zuza@rau.ac.uk

Abstract

Climate change and soil degradation threaten agricultural productivity in Sub-Saharan Africa (SSA), particularly in Malawi where smallholder farming systems predominate. This study presents a comparative assessment of deep bed farming (DBF) a hybrid conservation agriculture practice versus conventional ridging (CR) in smallholder maize-based farming systems through participatory on-farm quasi-experiments that positioned farmers as co-researchers. Across diverse agroecological zones, we implemented a randomized complete block design under farmer management to systematically evaluate both cultivation methods. DBF significantly ($p \leq 0.001$) outperformed CR, supporting higher plant populations of 450 vs 350 maize plants per 10 m² (45,000 vs. 35,000 plants ha^{-1}), higher stalk biomass yield of 75 vs. 50 kg per 10 m² (7,500 vs. 5,000 kg ha^{-1}), and 70% greater grain yields (8.5 – 9.0 vs. 5.0 metric tonnes ha^{-1}). These outcomes are attributed to DBF's enhancement of soil structure, moisture retention, and biological activity. The co-creation approach validated DBF's agronomic benefits while fostering local ownership, enabling real-time adaptation and enhancing adoption potential. Our findings highlight DBF as a scalable, climate-resilient practice capable of strengthening food security and ecological sustainability in resource-constrained smallholder systems.

Keywords: Deep bed farming, sustainable agriculture, climate resilience, maize productivity

Graphical abstract



1. Introduction

Climate change, loss of biodiversity and population pressures are undermining agricultural productivity across Sub-Saharan Africa (SSA) countries, with Malawi facing critical challenges. Despite agriculture being Malawi's economic backbone, persistent food insecurity and acute poverty continue to afflict millions of Malawians annually (FAO, 2022; Mgomezulu et al., 2024). The seriousness of this situation was illustrated in 2024, when the Malawi Vulnerability Assessment Committee (MVAC) reported over 6 million Malawians experiencing food insecurity, with more than 4 million facing a hunger crisis (IPC, 2024). Simultaneously, maize prices, the nation's staple crop, soared by over 230%, raising inflation to around 35% (FEWS NET, 2024).

These challenges are intensified by poor farming methods, such as traditional ridge-based systems, which result in the formation of an impermeable hard pan that is formed by continuous tillage at about 15 – 20 cm soil depth. Over time, this has significantly contributed to land degradation and the long-term decline in crop productivity (Mloza-Banda & Nanthambwe, 2010; Joyce et al., 2016; FAO, 2022). Malawi's heavy reliance on rainfed agriculture further amplifies the system's vulnerability to climate-induced disruptions, including increasingly frequent droughts, rising temperatures, and erratic rainfall patterns. These factors collectively contribute to an alarming 20% annual decline in crop yields (Mgomezulu et al., 2024), necessitating urgent interventions that address both immediate food security concerns and long-term agricultural sustainability.

While conservation agriculture (CA), emphasizing minimal tillage, soil cover and crop rotations has gained popularity as a sustainable alternative, its adoption in Malawi has been impacted by the persistent hardpans from historical tillage practices which negate the benefits of reduced soil disturbance (Andersson & D’Souza, 2014). In response, DBF emerges as a novel, systems-level innovation tailored to Malawi’s unique agroecological constraints. Developed and promoted by Tiyeni Malawi, DBF uniquely integrates a one-off strategic deep tillage (30 cm) with sustained CA principles (Mvula & Dixon, 2021; Tiyeni, 2023). This approach directly targets the root cause of degradation by fracturing hardpans to restore hydrological function and root penetration, while subsequent zero-tillage and organic mulching preserve soil structure and fertility long-term (Phiri et al., 2024). Unlike conventional CA systems, DBF's dual focus on immediate soil rehabilitation and sustained conservation offers a breakthrough solution for smallholders burdened by degraded lands and climatic volatility.

Early evidence highlights DBF's transformative potential. Trials by Mvula (2021) reported maize yield increases of 40–60% compared to ridge-based systems, while Phiri et al. (2024) demonstrated that DBF-enhanced soils exhibit 30% higher organic carbon and 50% greater water retention after three seasons. Crucially, DBF's labour-efficient design, requiring no annual deep tillage, aligns with the economic realities of resource-constrained farmers, a stark contrast to conventional ridge farming's repetitive labour demands. However, existing studies remain limited to controlled on-station trials or localised lead-farmers, leaving critical gaps in understanding DBF's scalability, on-farm variability, and socioeconomic viability.

Despite encouraging results from controlled on-station trials and lead farmer implementations, understanding DBF's broader on-farm impacts remains crucial for scaling this approach. Comparative analyses between DBF and traditional ridge-based farming systems can provide essential insights into its real-world effectiveness, enabling appropriate adaptation for resource-constrained smallholder farmers. Such evidence-based approaches could help address both immediate food insecurity and long-term agricultural sustainability challenges while fostering climate-resilient farming practices across Malawi. The study aims to compare DBF with CR systems to assess DBF's potential for enhancing crop yields and promoting soil conservation through rigorous on-farm quasi-experiments.

2. Materials and methods

2.1. Description of study sites

Malawi is a nation located in southern Africa. It has an area of 118, 484 km^2, with 94, 449 km^2 (80%) of land area and 24, 035 km^2 (20%) of water surface. The elevation ranges from 32 m in the south to 3, 002 m at the peak of Mount Mulanje in the southeast (Manja et al., 2025). The landscape is diverse, characterized by a mosaic of highlands encompassing mountains and plateaus, as well as lowland areas spread across the Central, Northern, and Southern regions (Figure 1a).

Malawi's climate is subtropical, distinguished by two seasons. The rainy season, which occurs between November and April, brings most of the annual rainfall, with the peak precipitation falling during the austral summer months of December, January, and February (Tholo et al., 2025). Figure 1b shows the spatial distribution of temperature and precipitation across the country. Temperature (°C) is represented along the horizontal axis, transitioning from cooler (blue) to warmer (orange), and precipitation (mm) is represented along the vertical axis, transitioning from low precipitation (light shades) to high precipitation (darker shades, particularly green).

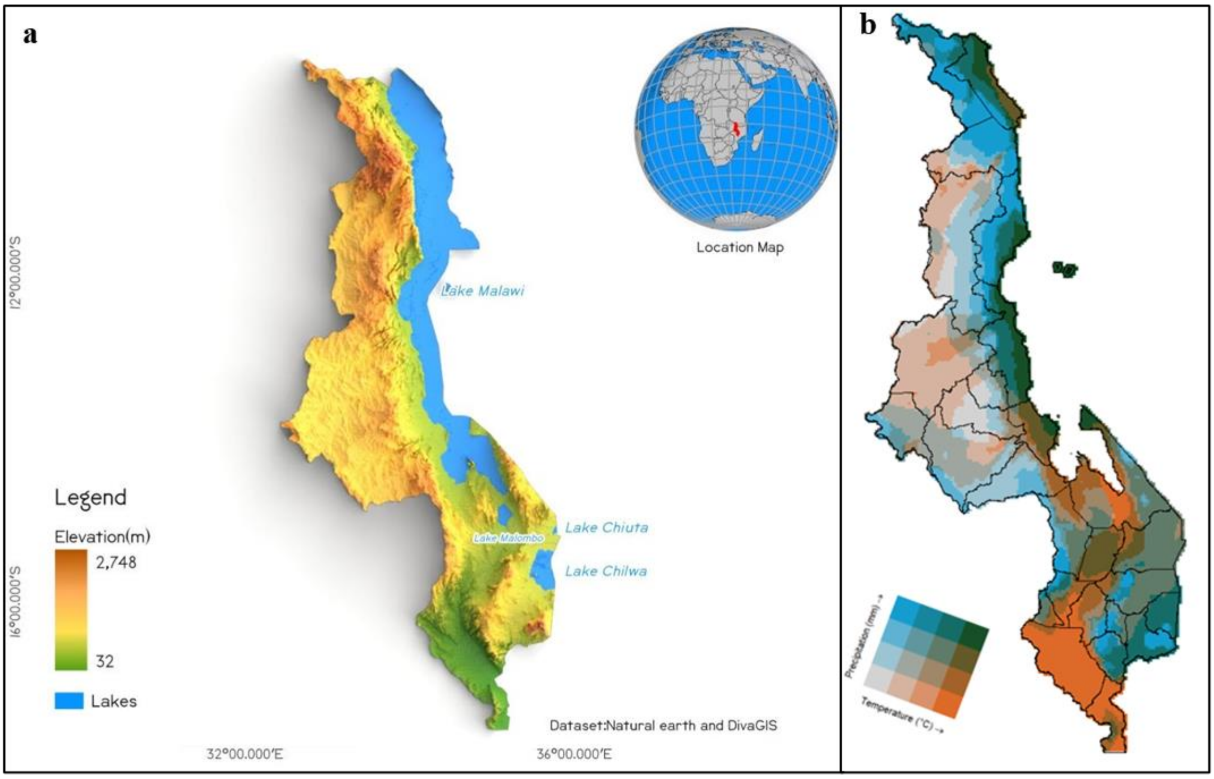


Figure 1: a) Map of Malawi showing topography variations b) Temperature and precipitation

Northern Malawi is characterised by generally cooler temperatures (17–25°C) and higher average rainfall amounts (1000–1600 mm) compared to the rest of the country. The study areas in this region include Bwengu, Chikwina, Chitheka, Emsizini, Eswazini and Manyamula extension planning areas (EPA, Figure 2). The elevated topography of these northern highlands plays a crucial role in moderating temperatures and enhancing precipitation through orographic effects, where moist air is forced upward along mountain slopes, cooling and condensing to form clouds and precipitation. These conditions create a relatively consistent climate pattern that supports different vegetation and agricultural practices than those found in the warmer south.

The Central region of Malawi experiences moderate to average cool temperatures (19–28°C) with moderate to high precipitation levels (800–1200 mm). The study areas in this region, as shown in Figure 2, include Madisi and Chiwamba EPAs. The central plateau where these sites are located creates varied microclimates depending on specific elevation and exposure, though generally maintaining cooler conditions than the southern lowlands. These study sites represent the transitional zone between the cooler north and hotter south, with climate conditions reflecting this intermediate position both in temperature patterns and precipitation regimes.

Southern Malawi exhibits significantly hotter average temperatures (22–32°C, particularly in the lowland areas that include some of the country's lowest elevations. In this region, the highlighted study areas include Kamwendo, Msikawanjala and Thuchila EPAs. This region receives lower rainfall (500–1000 mm) compared to the central and northern parts of the country, creating more challenging conditions for certain types of agriculture and ecosystem development. However, the presence of Mount Mulanje near the southern study sites creates a notable exception to the general pattern, as this massive elevation rise generates its microclimate with cooler temperatures and potentially higher rainfall than the surrounding southern lowlands.

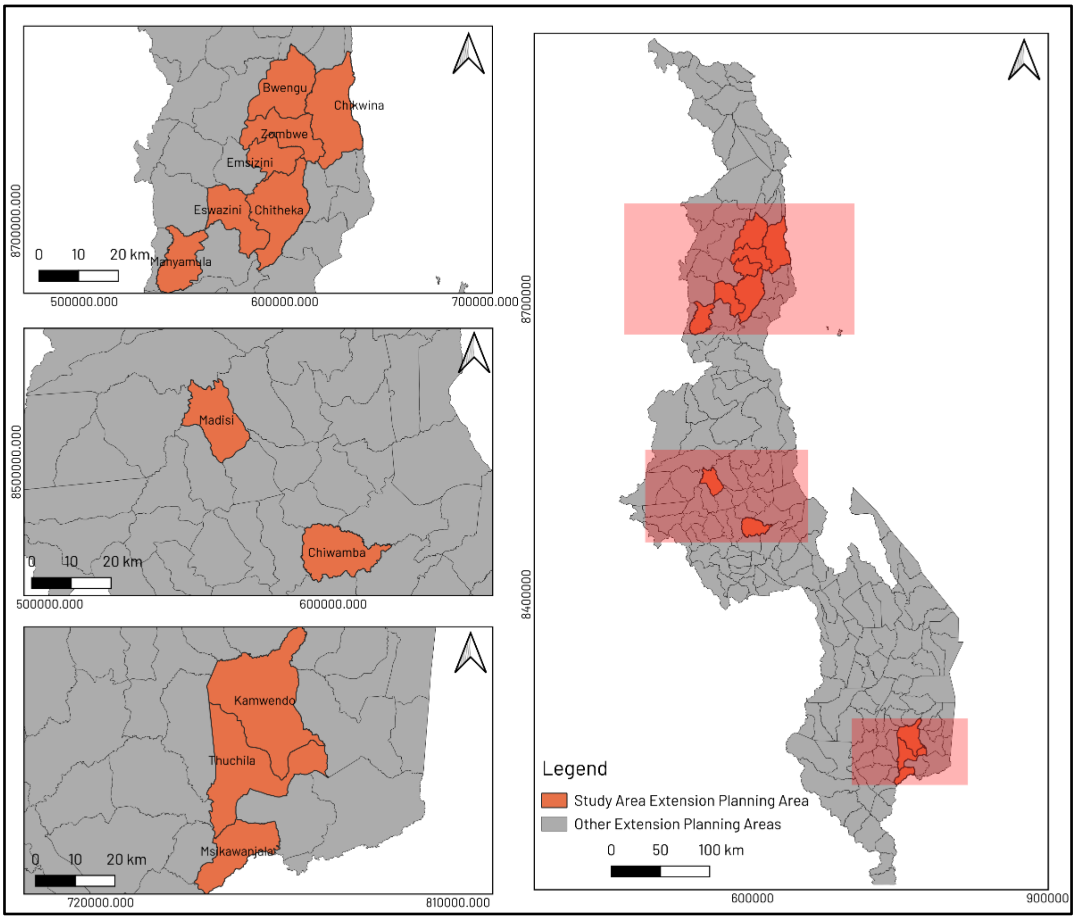


Figure 2: Study extension planning areas

2.2. Design of deep bed farming system

The implementation of the Tiyeni deep-bed farming system within a community follows a structured and collaborative approach. The process begins when interested farmers reach out to Tiyeni representatives, either local field officers or the Tiyeni Office to formally request assistance in adopting the method. Once a request is received, Tiyeni organises a meeting with the interested farmers. This meeting takes place in the presence of the Village Development Committee (VDC) and is overseen by the Group Village Headman (GVH), ensuring local leadership is involved from the outset. Following this, the GVH and local chiefs allocate a piece of land to be used as a demonstration field for co-generation of knowledge.

The demonstration field serves as a practical training site where farmers are introduced to and gain hands-on experience with the deep-bed farming system. This training spans one full growing season. During this period, Tiyeni supplies the necessary knowledge, skills, and equipment required for successful implementation. Farmers, in turn, contribute voluntarily by dedicating about two hours per week of their time and labour to the demonstration field. Importantly, all produce harvested from the garden are retained by the participating farmers, providing both immediate benefits and long-term skills for sustainable farming.

The DBF system itself involves the construction of carefully designed seedbeds, each one metre wide and raised to a height of 30 cm (Figure 3). Furrows are spaced 30 cm apart at the base and 50 cm at the top to optimize planting and water management. These seedbeds are further supported by box ridges constructed every 15 to 25 metres (Tiyeni, 2023). The box ridges serve dual purposes: they provide convenient pathways for farmers to access their crops and help conserve rainwater within the field. By limiting runoff and reducing soil erosion, these features enhance both water retention and soil fertility, making the DBF system an effective and sustainable approach to smallholder farming.

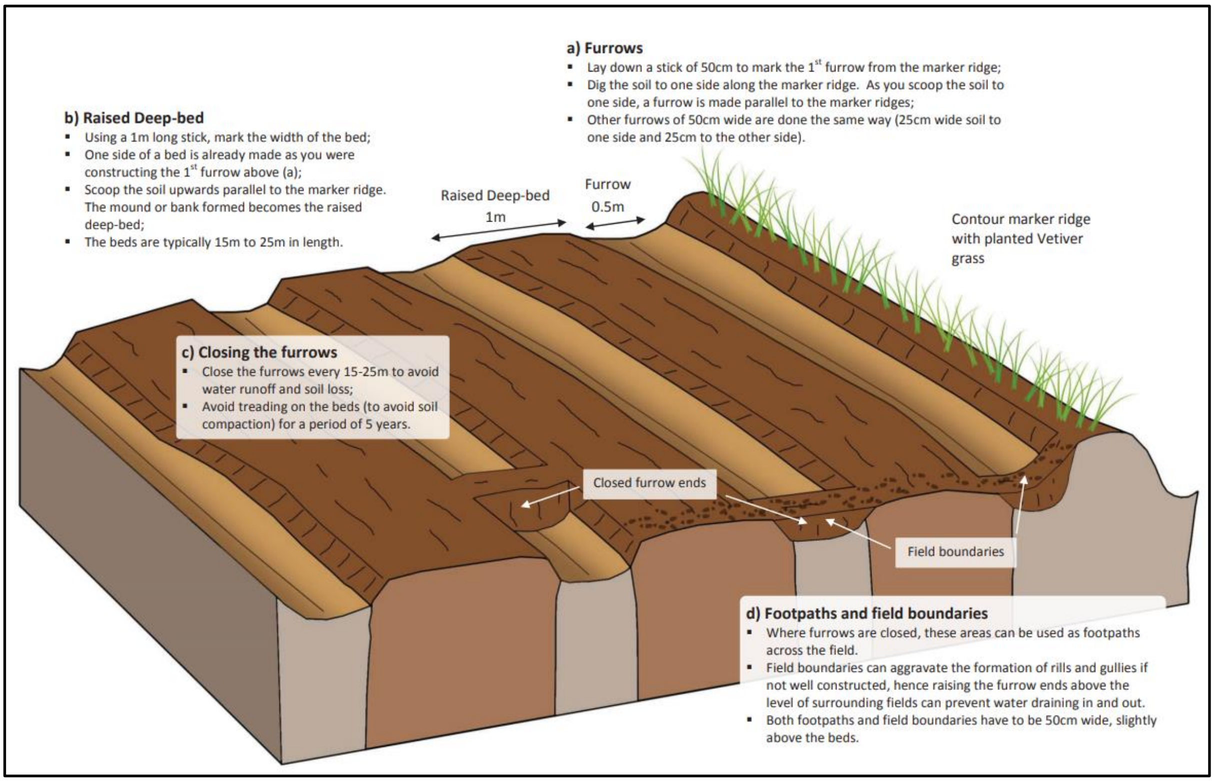


Figure 3: An illustration of the DBF system (Mvula & Dixon., 2021).

2.3. Experimental design

We used a quasi-experimental participatory research approach to assess the comparative impacts of DBF and CR on maize yields in smallholder agricultural systems in Malawi. A randomised complete block design was used, with EPAs serving as blocks and farmer fields as replicates within each block. This methodological approach was strategically selected to capture the variability of smallholder farming contexts while maintaining scientific rigour. Within each participating farmer's field, 10 m × 10 m net plots were systematically demarcated for both DBF and CR farming treatments, ensuring standardised yield determination procedures. One maize seed was planted per station, spaced 25 cm apart within rows and 75 cm between rows.

All trials were conducted under rainfed conditions with consistent agronomic management practices across sites, though with minor variations reflecting local contexts. Planting was done with the onset of reliable rains between mid-November and early December, with harvesting in April-May. Manual weeding was performed twice during the growing season.

Our study was conducted over seven growing seasons (2018, 2019, 2020, 2023, and 2024) in collaboration with Tiyeni member farmers and the Department of Agriculture Research Services (DARS), Ministry of Agriculture. Data from 2015, 2016, 2017, 2021 and 2022 were excluded from analysis because farmers received maize seed late, which significantly delayed planting and impacted yields. This longitudinal timeframe allowed for robust assessment of agricultural interventions across multiple environmental and seasonal variations.

Central to the research was an engaged approach that transcended traditional extractive research models. Lead farmers who are members of Tiyeni were positioned as co-researchers and knowledge partners, actively participating in developing contextualised action plans, coordinating data collection processes, providing local insights, and facilitating knowledge transfer within their farming communities. This participatory methodology addressed key limitations in traditional agricultural research by empowering local farmers as active knowledge producers, ensuring research relevance to local contexts, building local technical and analytical capacities, and facilitating sustainable knowledge dissemination.

The involvement of lead farmers contributed valuable insights from non-scientific perspectives, which have been instrumental in substantiating, elucidating, and triangulating our findings. This collaborative approach has established a comprehensive and reliable knowledge base regarding the performance of the DBF in real-world farming conditions.

2.4. Plant growth and determination of yields

In the four cropping seasons, plant population and harvesting were conducted within a defined net plot of 10 m x 10, which was obtained by leaving 1 m as a buffer on all sides to eliminate edge effects from environmental interference and the total gross plot was 12 m x 12 m. This approach followed standard agronomic protocols to minimise edge effects and ensure the integrity of the experimental data. Plant population counts were carried out one week after germination to assess early establishment.

At physiological maturity, maize was harvested from the net plots, and grain yield as well as yield components (including cob number and total above-ground biomass) were carefully measured and recorded to evaluate system performance. Fresh grain yield was determined by shelling all cobs and weighing the grain, with moisture content adjusted to a standardized 12.5% using a grain moisture meter. Final yields were extrapolated to kg per ha using the net plot area, accounting for plant population variability.

2.5. Data analysis

The collected data were subjected to analysis of variance (ANOVA) using R® Statistical Computing Software version 4.5.0 (R Core Team, 2025). Treatment differences were compared using the Least Significant Difference (LSD) test at a 5% significance level ($p \leq$

0.05). Additionally, Newman-Keuls multiple range test was used to further distinguish significant differences among treatment means. All statistical analyses were performed following verification that the data met the assumptions of normality and homogeneity of variance.

3. Results

Maize productivity depends on numerous factors including weather conditions, soil properties, and agronomic practices, subsequently optimising these can significantly enhance yields. Below we present findings of our study evaluating the impact of DBF technology compared to CR in terms of crop yield attributes and overall yields. In addition, we incorporated farmers' perspectives to support the empirical evidence.

3.1. Plant population

A key determinant of maize productivity is plant population density, which directly influences resource utilization and final yields. The yearly comparison reveals clear performance differences between DBF and CR systems across multiple growing seasons. In 2018, although DBF showed numerically higher plant populations of 480 plants per 10 m^2 (48,000 plants ha^{-1}) compared to 390 plants per 10 m^2 (39,000 plants ha^{-1}), the difference was not statistically significant. By 2019, there were significant differences ($p \leq 0.05$), with DBF maintaining higher plant populations (450 plants per 10 m^2 or 45,000 plants ha^{-1}) compared to CR (385 plants per 10 m^2 or 38,500 plants ha^{-1}).

The advantage of DBF became more pronounced in subsequent years. In 2020, highly significant differences ($p \leq 0.001$) were observed, with DBF supporting substantially higher plant populations (390 plants per 10 m^2 or 39,000 plants ha^{-1}) compared to CR (290 plants per 10 m^2 or 29,000 plants ha^{-1}). This pattern continued in 2023 and 2024, both showing highly significant differences ($p \leq 0.001$) between systems, with DBF consistently maintaining higher plant densities (490 vs. 360 plants per 10 m² or 49,000 vs. 36,000 plants ha^{-1} in 2023; 500 vs. 380 plants per 10 m² or 50,000 vs. 38,000 plants ha^{-1} in 2024).

Notably, years with more challenging weather conditions appeared to magnify the advantages of DBF over CR (particularly evident in 2020, 2023, and 2024), suggesting its potential as a climate-resilient practice for smallholder farmers. The interquartile ranges shown in the boxplots indicate that DBF not only supports higher overall plant populations but also demonstrates greater stability across different field conditions.

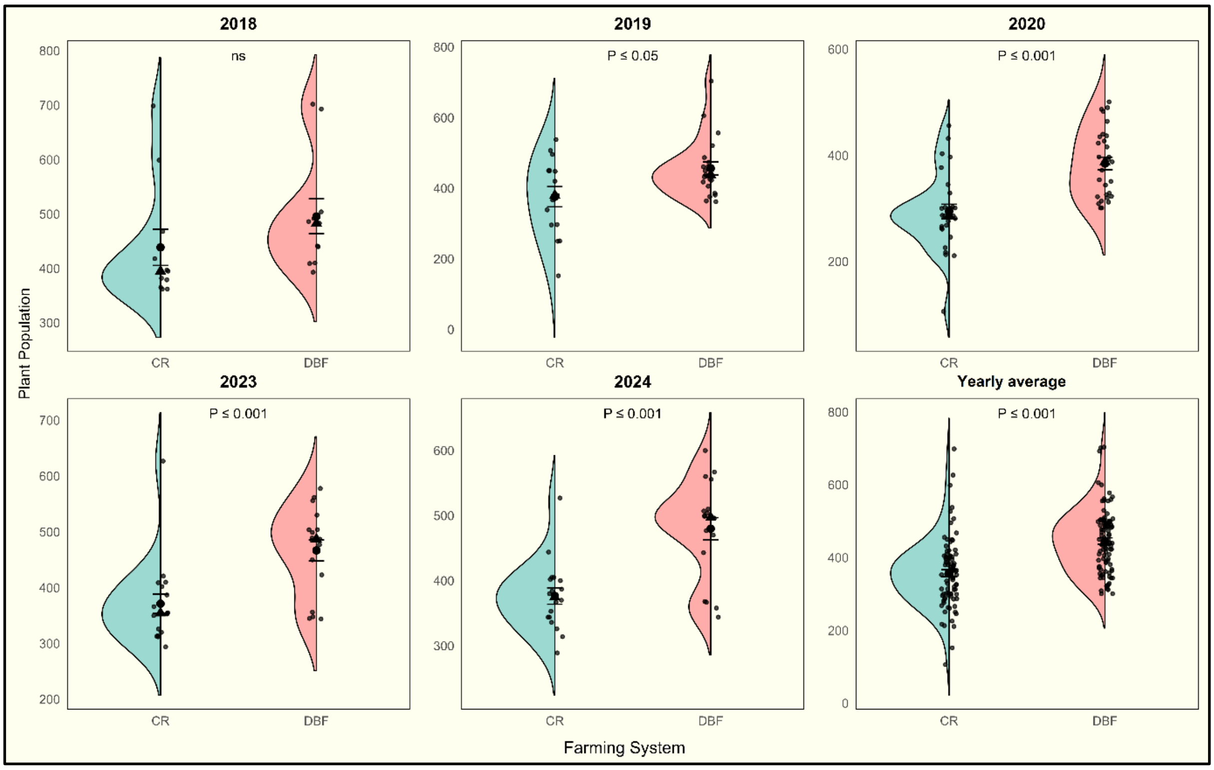


Figure 4: Plant population between DBF and CR systems.

3.2. Stalk biomass

Stalk development in maize represents a critical indicator of overall plant health, nutrient availability, and system productivity. The comparison of dry maize stalk weight between DBF and CR systems reveals significant differences across multiple growing seasons (Figure 5). In 2018, maize grown in DBF plots produced an average dry stalk biomass of approximately 75 kg per 10 m² (7.5 Mt ha⁻¹), compared to just 50 kg per 10 m² (5 Mt ha⁻¹) in CR systems, representing a 50% increase in above-ground biomass ($p \leq 0.05$). This trend was further amplified in 2019 and 2020, with DBF plots averaging 85 – 90 kg per 10 m² (8.5 – 9 Mt ha⁻¹), while CR plots remained substantially lower, around 55 kg and 50 kg per 10 m² (5.5 and 5 Mt ha⁻¹), respectively ($p \leq 0.001$ for both years).

However, in 2023 and 2024, although DBF continued to produce heavier stalks than CR, the differences were not statistically significant. The median stalk weights for DBF in these years remained higher (approximately 60 kg per 10 m² or 6 Mt ha⁻¹ in 2023 and 70 kg per 10 m² or 7 Mt ha⁻¹ in 2024) compared to CR (55 kg per 10 m² or 5.5 Mt ha⁻¹ in 2023 and 60 kg per 10 m² or 6 Mt ha⁻¹ in 2024).

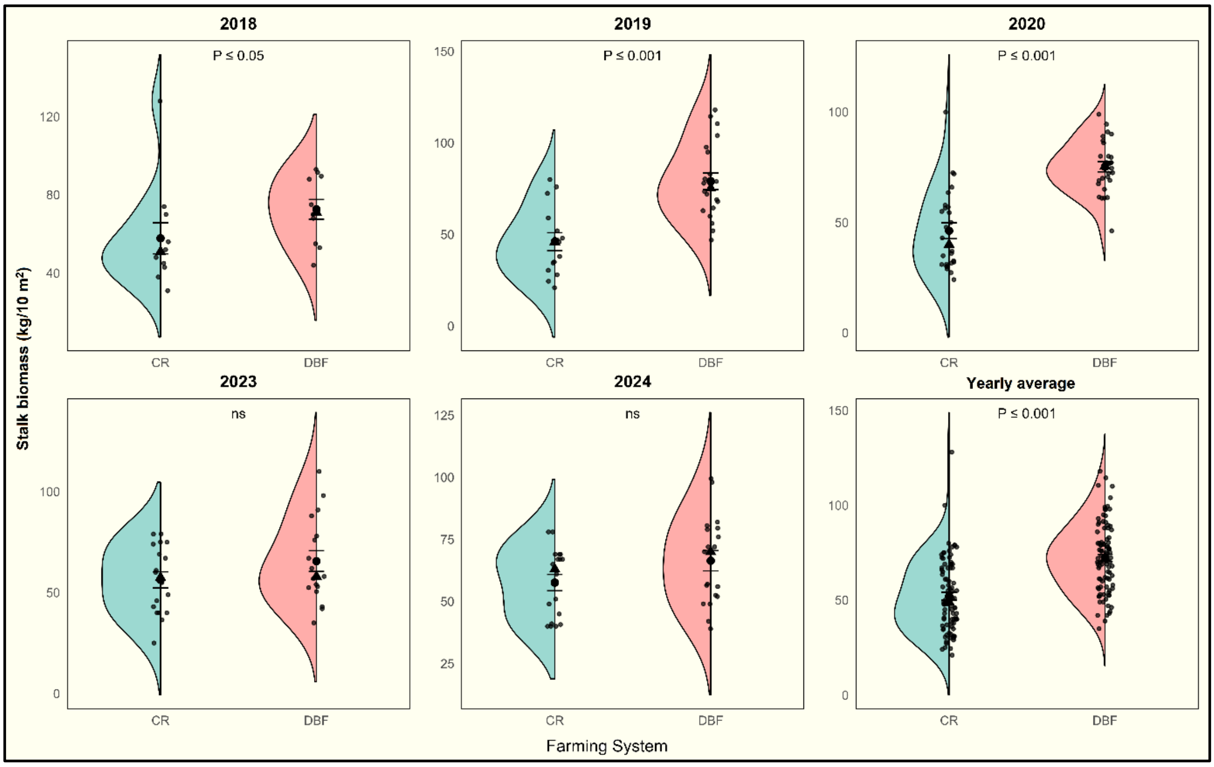


Figure 5: Maize stalk biomass as influenced by tillage system.

3.3. Number of cobs

The number of maize cobs per plot is a direct indicator of productive capacity and yield potential. Figure 6 presents a comparative analysis of cob production between the two systems evaluated in this study. It can be observed that in 2018, DBF plots had a significantly higher cob count compared to CR ($p \leq 0.01$). This trend is pronounced in subsequent years, with highly significant differences ($p \leq 0.001$) observed from 2019 through 2024. Notably, the 2019 season showed DBF plots producing median cob counts of approximately 500 (50, 000 cobs ha^{-1}), compared to 300 (30, 000 cobs ha^{-1}) in CR plots (Figure 6). Similarly, in 2020, DBF plots yielded around 400 (40, 000 cobs ha^{-1}) cobs per plot versus 250 (25, 000 cobs ha^{-1}) in CR plots. The difference remained consistent in later seasons, with 2023 showing median values of 510 cobs (1, 000 cobs ha^{-1}) for DBF compared to 320 (32, 000 cobs ha^{-1}) for CR, and 2024 showing approximately 520 (52, 000 cobs ha^{-1}) cobs for DBF versus 320 (32, 000 cobs ha^{-1}) for CR. Christina Thom a farmer from Kamwendo EPA indicated:

> "I harvested a cob from every maize plant in my field. I can confidently say that DBF has proven to be a very good technology, especially during times of drought. While all other technologies were badly affected by the dry spells, DBF performed very well in my field".

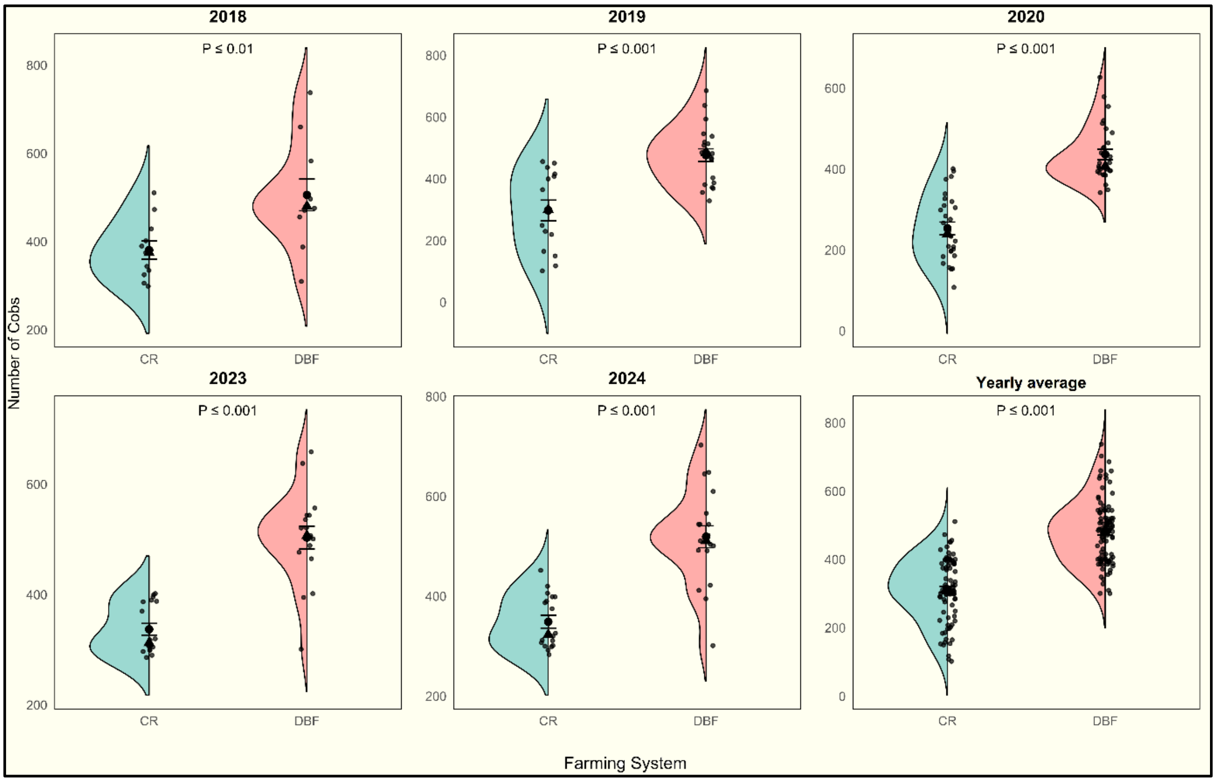


Figure 6: Number of cobs per 10 m^2 as influenced by tillage system.

3.4. Crop yield

Yield improvements are a critical measure of the effectiveness of any agricultural system. Our analysis revealed consistently higher maize yields under DBF compared to CR across most seasons (Figure 7). DBF plots produced an average of approximately 50,000 cobs ha^{-1}, while CR plots yielded around 30,000 cobs ha^{-1}. These increases in cob production were accompanied by substantial and statistically significant differences in grain yield across multiple years. From Figure 7, it is observed that in 2018, DBF maize yields ranged between 85 – 90 kg per 10 m^2 (8.5 – 9 Metric tonnes/Mt ha^{-1}), compared to approximately 50 kg under CR (5 Mt ha^{-1}), representing a ~70% yield increase ($p \leq 0.01$). The yield advantage was pronounced in 2019 and 2020 ($p \leq 0.001$), with DBF systems achieving average yields exceeding 9 Mt ha^{-1}, while CR systems remained below 6.0 Mt ha^{-1}.

Farmer testimonials further validate these substantial yield improvements. Eliya Ndhlovu from Emsizini EPA stated:

> "DBF is a promising practice for all smallholder crops guaranteeing increased yields. Because of this, I will continue converting my farm to DBF."

Another farmer, Mr. Mbeya from the same EPA, who has implemented the DBF system for approximately 10 years, reported:

> "I am happy to have adopted DBF. It is assuring good yields every year."

These cases demonstrate both the immediate productivity benefits and long-term sustainability of DBF systems, with significant implications for agricultural development and improved farmer livelihoods throughout the region.

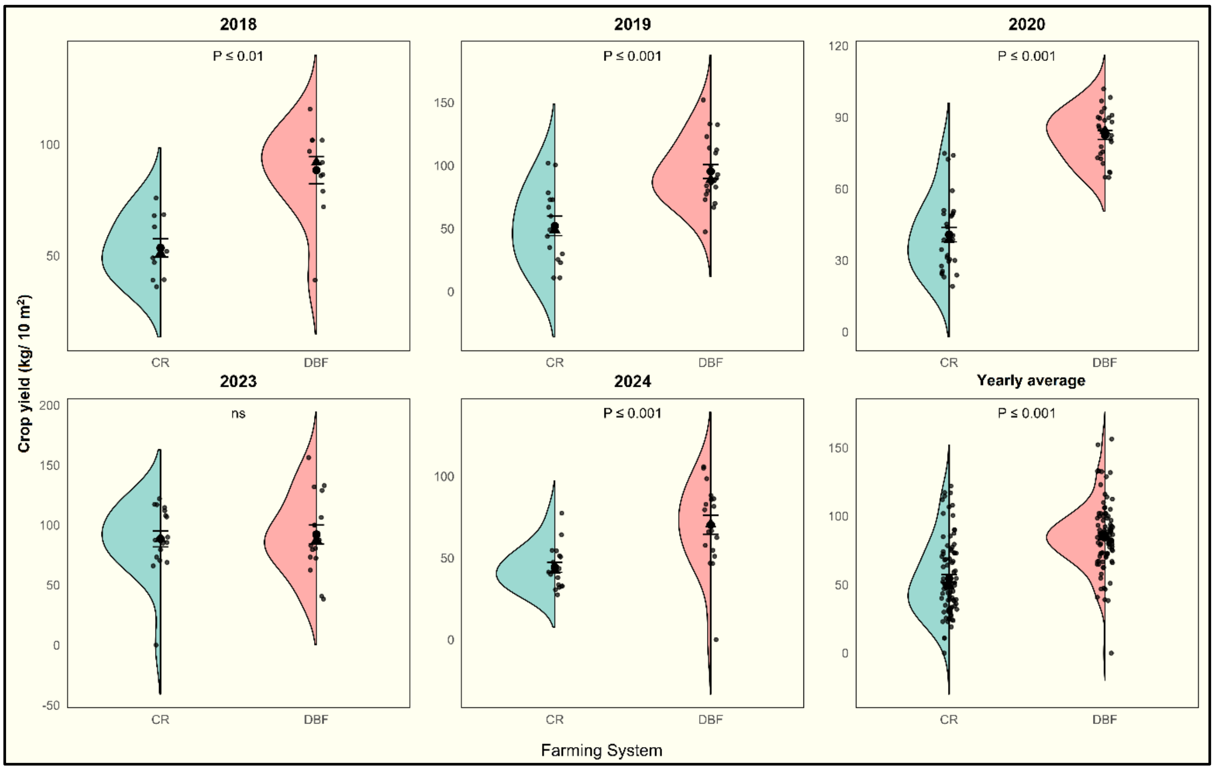


Figure 7: Maize yield as influenced by tillage system.

3.5. Principal component analysis

The first two principal components collectively accounted for 20.4% of the total variability (Dim1: 11.1%; Dim2: 9.3%). The analysis revealed significant ($p \leq 0.001$) insights into how farming practices and environmental factors influence maize productivity. DBF consistently outperformed CR farming across various EPAs in Malawi (Figure 8). Highest yields in DBF systems are observed in the later years (2022 – 2024) after adoption of the technology compared to earlier years (2018 – 2020). This temporal shift suggests that the soils under DBF are recovering and hence leading to increased crop productivity.

Specific yield data on EPAs shows varying results, which is attributed to agroecological conditions. For example, in Emsizini EPA there were yield increases, with maize production more than doubling than other EPAs. This highlights how DBF's benefits can vary depending on the local environment. Other EPAs, such as Bwengu, Chikwina, and Chitheka, likely experience similar trends, though the magnitude of yield improvement may differ based on their specific agroecological characteristics, such as soil type and rainfall distribution.

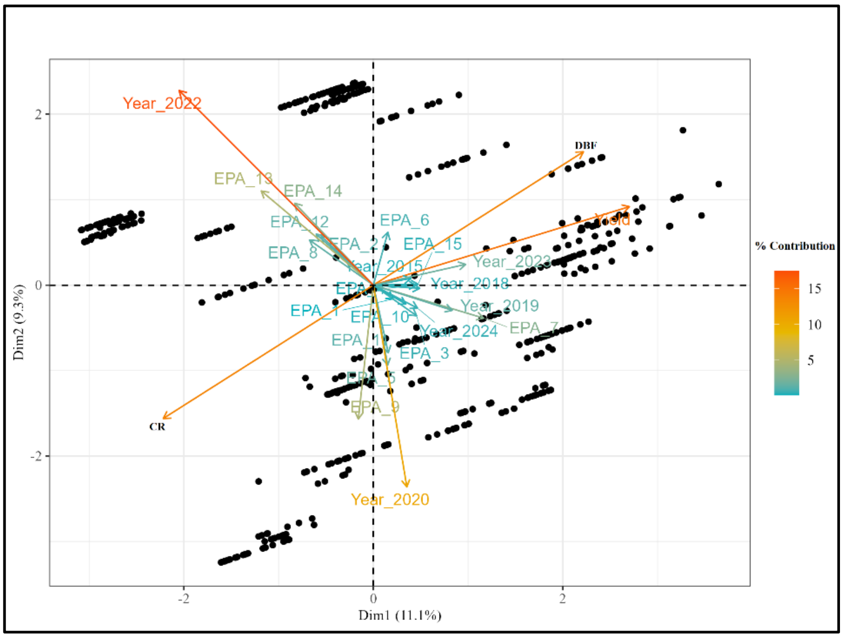


Figure 8: Multivariate analysis on the influence of farming system and EPA on maize yield.

4. Discussion

The findings of our study provide compelling evidence that DBF significantly outperforms CR in maize productivity among smallholder farming communities in Malawi. These results demonstrate DBF's potential as an effective CA practice with important implications for enhancing food security.

A fundamental advantage of DBF over CR is its ability to enhance soil physical properties and biological activity, leading to better root establishment and overall plant performance. Whilst measurement of the soil parameters was not done as part of the current study, earlier research has shown significant improvements in soil aeration and moisture retention under DBF compared to CR (Mvula and Dixon, 2021; Phiri et al., 2024). Our correlation analysis further supports this finding, with plant population showing a moderate positive correlation with yield in both systems. Notably, DBF consistently demonstrated stronger correlation coefficients, suggesting that the improved soil conditions under DBF effectively translated plant population density into yield gains. This evidence aligns with insights from farmers themselves, as one participant reported:

> "The measurements in the beds [DBF] are precise and calculated, whereas farming on ridges lacks such precision. As a result, beds seem to accommodate a higher number of maize plants within the plots of the same size compared to ridges. While I have not yet counted the plants to confirm this, I am confident that my observation is true".

Moreover, Mvula (2021) reports that farmers identified a significantly higher plant population in the DBF plots compared to the CR plots. This observation, as stated by the farmers, was associated with enhanced crop productivity. The findings of this study corroborate the farmers' previous assessments. Unlike CR, which often results in soil compaction and restricted root growth due to repeated shallow ploughing (Thierfelder et al., 2022; Nyamayevu et al., 2025; Manzeke-Kangara et al., 2025), DBF promotes looser, well-aerated soils that allow for deeper root penetration and more efficient nutrient uptake (Phiri et al., 2024).

The improvement in soil structure directly supports enhanced biological activity in DBF systems by fostering greater microbial diversity, which in turn facilitates improved organic matter decomposition and nutrient cycling. Mirzavand et al. (2022) demonstrated that reduced tillage systems like DBF preserve soil microbial communities and enhance their functionality. Conversely, CR disrupts these soil microbial networks through frequent soil disturbance, resulting in lower organic matter retention and reduced long-term soil fertility, leading to severe soil degradation (Mloza-Banda et al., 2016; Ahamefule et al., 2020; Manzeke-Kangara et al., 2025).

The possibility of enhanced soil health in DBF is reflected in our findings of higher dry stalk biomass, indicating better vegetative growth which may be due to nutrient and water availability consistent with findings from other CA studies in similar agroecological zones (Ngwira et al., 2013; Bouwman et al., 2021; Nyagumbo et al., 2024). Building on these soil structural improvements, DBF systems demonstrate superior water management capacity by enhancing capillary movement of moisture from deeper soil horizons due to the elimination of hardpan layers in CR.

The improved soil architecture leads to significantly better water retention, a critical factor for smallholder maize farming in regions experiencing erratic rainfall patterns (Dixon et al., 2017). This enhanced moisture conservation ensures that crops have sustained access to water, thereby reducing drought and flood stress and improving yield stability (TerAvest et al., 2015; Choudhary et al., 2017; Mupangwa et al., 2022). The higher plant populations observed in our DBF plots further confirms that this system provides a more stable environment for plant establishment even under varying moisture conditions. The climate resilience of DBF was powerfully illustrated during extreme weather events in 2020, 2023 and 2024 growing season, as evidenced by a farmer from Komwa village who reported:

> "Crops under DBF were resilient in the floods, to the extent that my crops and beds were not washed away with the flooding. If I had not adopted DBF, I would not have survived the impact of Cyclone Freddy in terms of food. Even though the water was too much, I managed to harvest two and a half bags of maize from the [Deep] Beds".

In contrast, CR often exacerbates moisture stress, as conventional ridges typically lead to uneven water distribution, reduced rainwater infiltration, increased surface runoff and soil erosion, causing waterlogging in some areas while others experience excessive drying (Ngetich et al., 2014; Wolka et al., 2018; Nyagumbo et al., 2020). Studies by Hermans et al. (2021) and Oliveira et al. (2024) have demonstrated that conservation agriculture practices like DBF can significantly increase water infiltration rates and reduce runoff by up to 45% compared to conventional tillage systems. This ability to moderate soil moisture fluctuations makes DBF a particularly valuable cropping system under the increasingly unpredictable rainfall patterns associated with climate change in SSA. A farmer from Jalanthowa village indicated:

> "The bed, being more spacious and thoroughly tilled, offers better water retention compared to ridges. Harvested water remains localised in the plot, enabling the bed to provide moisture to crops during mid-season droughts which are more frequent in recent years. By the time beds lose all the moisture, another rainfall is likely to have occurred".

Figure 9: In field benefits of DBF

The most compelling evidence of DBF's superiority over CR is seen in the substantial yield improvements. DBF plots had a higher maize yield potential of 8.5 – 9.0 Mt ha^{-1} than those observed in CR systems. These findings are particularly relevant in the context of smallholder maize farming in Malawi, where current yields remain well below their potential. While the USDA Foreign Agricultural Service estimates the national average maize yield in Malawi between 2019/20 and 2023/24 at 2.12 Mt ha^{-1} (including large-scale commercial farms), smallholder farmers typically achieve yields of only 1 – 1.7 Mt ha^{-1} (Anghileri et al., 2024). These yields represent a fraction of the 4 – 13 Mt ha^{-1} potential achievable under improved agronomic conditions.

The yield advantages observed in our DBF plots align with broader CA research across SSA. Namatsheve et al. (2024) revealed that CA practices can increase maize yields by 20 – 60% in rain-fed systems, particularly in low-rainfall environments. Furthermore, CR accelerates soil degradation through repeated tillage and erosion whereas DBF fosters soil resilience and long-term fertility, ensuring sustained high yields over multiple cropping seasons (Phiri et al., 2024).

The benefits of DBF extend beyond immediate yield improvements to broader implications for climate resilience and sustainable agriculture in Malawi. By enhancing soil moisture retention and biological activity, DBF effectively helps mitigate climate-induced risks such as prolonged dry spells and erratic rainfall patterns.

Given the mounting challenges posed by climate change in SSA, widespread adoption of DBF could play a pivotal role in stabilising maize yields, improving soil health, and ensuring long-term agricultural sustainability in smallholder farming systems. From an economic perspective, conservation agriculture approaches like DBF provide additional benefits through reduced labour requirements and input costs over time, though initial implementation may require additional resources and knowledge (Mvula and Dixon, 2021).

4.1. Implications

The on-farm experimentation approach used in this study served as a powerful mechanism for both technical design improvement and farmer engagement. By establishing demonstration plots directly within farming communities, researchers were able to adapt the DBF technology to suit local soil conditions, tool availability, and farmer capabilities. This participatory approach allowed farmers to witness first-hand the development process, contribute their indigenous knowledge to plot design, and observe the technology's performance through various growth stages. The transparency of this process significantly enhanced farmer buy-in for DBF, as community members could directly compare conventional practices with the new technology under familiar conditions.

The demonstration plots functioned not only as research sites but also as living classrooms where farmers gained hands-on experience with DBF techniques. This experiential learning approach empowered communities with practical skills and knowledge, fostering a sense of ownership that is critical for sustainability beyond donor funding cycles. When farmers actively participate in technology development and see tangible benefits in their own environment, they become natural advocates and knowledge-sharers within their communities, creating pathways for scaling up (Morgans et al., 2021; Lacoste et al., 2022).

While our results strongly favour DBF implementation, they also highlight the need for further research to assess its long-term viability across different agroecological zones in Malawi and beyond. Future studies should explore economic feasibility and compatibility with complementary conservation practices, especially crop rotation, cover cropping and intercropping. Equally important is understanding farmer adoption barriers to ensure that smallholder communities have access to necessary training, resources, and policy support for successful implementation.

Longitudinal studies tracking soil health parameters, yield stability, and farmer perceptions over multiple seasons would provide invaluable insights into the sustained benefits of DBF under varying climatic conditions. Such research would strengthen the evidence base for policy advocacy and scaling efforts, ultimately promoting DBF as a climate-smart agricultural practice capable of transforming smallholder farming systems throughout Malawi and similar contexts across SSA.

To further strengthen sustainability, future initiatives should consider establishing farmer-to-farmer learning networks and creating mechanisms for community-based monitoring of DBF performance. These elements would help ensure that the technology remains accessible and effective even after external support ends, truly embedding DBF within the agricultural practices of smallholder communities.

5. Conclusions

Our study provides robust evidence that deep bed farming offers significant advantages over conventional ridging systems for smallholder farmers in Malawi. DBF consistently demonstrated superior performance across all measured parameters, including plant population density, biomass accumulation, and most importantly, grain yield. This suggests that the technology's ability to enhance soil structure, improve water retention, and foster biological activity directly translates to a 70% increase in maize productivity, with yields reaching 8.5 – 9 Mt ha^{-1} compared to 5 Mt ha^{-1} under conventional ridging.

These findings have important implications for addressing food security challenges in Malawi, where smallholder farmers typically achieve yields far below potential. By implementing DBF, farmers can potentially bridge this yield gap while simultaneously improving soil health and building resilience against climate variability. While our results are promising, further research on long-term sustainability, economic feasibility, and adoption barriers will be essential for successful scaling of DBF across diverse agroecological zones. Nevertheless, DBF represents a practical and effective climate-smart agricultural approach with transformative potential for smallholder farming systems throughout Malawi and similar contexts in SSA.

Data and code availability

The complete dataset and analysis code used in this study are publicly available and can be accessed in the "Malawi-Farming-Practices-Analysis" repository at https://github.com/WilliamBanda/Malawi-Farming-Practices-Analysis. This repository contains all raw data, processed datasets, statistical analysis scripts, and visualisation code used to generate the findings presented in this paper. We encourage other researchers to utilise these resources for verification, replication, or extension of our work.

Funding source

N/A

Acknowledgements

We are deeply grateful to the smallholder farmers who generously volunteered their time and land to trial the DBF system, participated in valuable discussions, and welcomed our research team with exceptional hospitality. Our sincere appreciation extends to the entire Tiyeni team for their tireless dedication in farmer training and meticulous data collection efforts throughout this study. Any errors or omissions in this paper remain solely the responsibility of the authors.

Authors Contributions

All authors contributed equally to the conceptualisation, methodology, investigation, data analysis, visualisation, and writing of this research paper. Each author participated substantially in all phases of this study from its inception through to manuscript preparation and revision.

References

Ahamefule, H. E., Eifediyi, E. K., Amana, M. S., Olaniyan, J. O., Ihem, E., Ukelina, C. U., & Fatola, F. O. (2020). Comparison of traditional and modern approaches to soil conservation in a changing climate: A review. *Bulgarian Journal of Soil Science Agrochemistry and Ecology, 54(1),* 44–62.

Anghileri, D., Chibarabada, T. P., Gadedjisso-Tossou, A., Craig, A., Li, C., Lu, Y., ... & Sheffield, J. (2024). Understanding the maize yield gap in Southern Malawi by integrating ground and remote-sensing data, models, and household surveys. *Agricultural Systems*, 218, 103962. https://doi.org/10.1016/j.agsy.2024.103962

Bouwman, T. I., Andersson, J. A., & Giller, K. E. (2021). Adapting yet not adopting? Conservation agriculture in Central Malawi. *Agriculture, Ecosystems & Environment*, 307, 107224. https://doi.org/10.1016/j.agee.2020.107224

Caruso, G., & Sosa, L. C. (2022). Poverty Persistence in Malawi: climate shocks, low agricultural productivity and slow structural transformation Malawi | Poverty Assessment.

Choudhary, R. L., Kumar, M., Kumar, S., Ram, H., & Kumari, A. (2017). Potential of Conservation Agriculture in Drought Stress Management in Crop Plants. *CCSA, 6(24),* 103-121.

FAO GIEWS Country Brief on Malawi -. (n.d.). Retrieved January 5, 2025, from https://www.fao.org/giews/countrybrief/country.jsp?code=MWI

FAO. (2022). Soil loss assessment in Malawi Government of Malawi Ministry of Agriculture, Irrigation and Water Development. www.fao.org/publications

Hermans, T. D., Dougill, A. J., Whitfield, S., Peacock, C. L., Eze, S., & Thierfelder, C. (2021). Combining local knowledge and soil science for integrated soil health assessments in conservation agriculture systems. *Journal of Environmental Management*, 286, 112192. https://doi.org/10.1016/j.jenvman.2021.112192

IPC, (2024) Climatic shocks, economic decline and high food prices drive acute food insecurity in rural and urban Malawi. Integrated Food Security Phase Classification (IPC) Acute Food Insecurity Analysis May 2024 - March 2025.

Lacoste, M., Cook, S., McNee, M., Gale, D., Ingram, J., Bellon-Maurel, V., McMillan, T., & Hall, A. (2022). On-farm experimentation to transform global agriculture. Nature Food, 3(1), 11–18. https://doi.org/10.1038/s43016-021-00424-4

Manja, L. P., Zingwe, D. E., & Kamangila, A. E. (2025). Smallholder farming commercialization and food security in Malawi: do land rights and intrahousehold bargaining power matter?. *Agriculture & Food Security, 14(1)*, 2. https://doi.org/10.1186/s40066-025-00520-9

Manzeke-Kangara, M. G., Ligowe, I. S., Tibu, A., Gondwe, T. N., Greathead, H. M., & Galdos, M. V. (2025). Soil organic carbon and related properties under conservation agriculture and contrasting conventional fields in Northern Malawi. *Frontiers in Soil Science*, 4, 1481275. https://doi.org/10.3389/fsoil.2024.1481275

Manzeke-Kangara, M. G., Ligowe, I. S., Tibu, A., Gondwe, T. N., Greathead, H. M., & Galdos, M. V. (2025). Soil organic carbon and related properties under conservation agriculture and contrasting conventional fields in Northern Malawi. *Frontiers in Soil Science*, 4, 1481275. https://doi.org/10.3389/fsoil.2024.1481275

Mgomezulu, W. R., Edriss, A. K., Machira, K., Pangapanga-Phiri, I., Chitete, M., Mambosasa, M., ... & Mnthambala, F. (2024). Understanding spillover effects of sustained adoption of sustainable agricultural practices on household resilience to food shocks: Evidence from Malawi's sustainable food systems program. *Journal of Agriculture and Food Research*, 16, 101099. https://doi.org/10.1016/J.JAFR.2024.101099

Mirzavand, J., Asadi-Rahmani, H., & Moradi-Talebbeigi, R. (2022). Biological indicators of soil quality under conventional, reduced, and no-tillage systems. *Archives of Agronomy and Soil Science, 68 (3),* 311-324. https://doi.org/10.1080/03650340.2020.1832656

Mloza-Banda, H. R., & Nanthambwe, S. J. (2010). Conservation agriculture programmes and projects in Malawi: Impacts and lessons. http://hdl.handle.net/10919/69913

Mloza-Banda, H. R., Makwiza, C. N., & Mloza-Banda, M. L. (2016). Soil properties after conversion to conservation agriculture from ridge tillage in Southern Malawi. *Journal of Arid Environments*, 127, 7-16. https://doi.org/10.1016/j.jaridenv.2015.11.001

Morgans, L. C., Bolt, S., Bruno-McClung, E., Van Dijk, L., Escobar, M. P., Buller, H. J., ... & Reyher, K. K. (2021). A participatory, farmer-led approach to changing practices around antimicrobial use on UK farms. *Journal of Dairy Science*, *104*(2), 2212-2230. https://doi.org/10.3168/jds.2020-18874

Mupangwa, W., Yahaya, R., Tadesse, E., Ncube, B., Mutenje, M., Chipindu, L., ... & Kassa, A. (2022). Crop productivity, nutritional and economic benefits of no-till systems in smallholder farms of Ethiopia. *Agronomy, 13(1)*, 115. https://doi.org/10.3390/agronomy13010115

Muyanga, M., Nyirenda, Z., Lifeyo, Y., & Burke, W. J. (2020). The future of smallholder farming in Malawi. Mwapata Institute. Working Paper, 20 (30). https://doi.org/10.13140/RG.2.2.33903.87201

Mvula, A. (2021). The social-ecological sustainability of the Tiyeni deep-bed conservation agriculture system in Malawi (Doctoral dissertation, University of Worcester).

Mvula, A., & Dixon, A. (2021). Farmer experiences of Tiyeni's 'deep-bed farming'conservation agriculture system in Malawi. *Agroecology and Sustainable Food Systems, 45(2)*, 175-196. https://doi.org/10.1080/21683565.2020.1819513

Namatsheve, T., Martinsen, V., Obia, A., & Mulder, J. (2024). Grain yield and nitrogen cycling under conservation agriculture and biochar amendment in agroecosystems of sub-Saharan Africa. A meta-analysis. *Agriculture, Ecosystems & Environment*, 376, 109243. https://doi.org/10.1016/j.agee.2024.109243

Ngetich, K. F., Diels, J., Shisanya, C. A., Mugwe, J. N., Mucheru-Muna, M., & Mugendi, D.

N. (2014). Effects of selected soil and water conservation techniques on runoff, sediment yield and maize productivity under sub-humid and semi-arid conditions in Kenya. *Catena,* 121, 288-296. https://doi.org/10.1016/j.catena.2014.05.026

Ngwira, A. R., Thierfelder, C., & Lambert, D. M. (2013). Conservation agriculture systems for Malawian smallholder farmers: long-term effects on crop productivity, profitability and soil quality. *Renewable Agriculture and Food Systems, 28(4)*, 350-363. https://doi.org/10.1016/j.agee.2020.107224

Njoloma, J. P., Sileshi, W. G., Sosola, B. G., Nalivata, P. C., & Nyoka, B. I. (2016). Soil fertility status under smallholder farmers fields in malawi. *African journal of agricultural research, 11(19)*, 1679-1687. https://doi.org/10.5897/ajar2015.10018

Nyagumbo, I., Mupangwa, W., Chipindu, L., Rusinamhodzi, L., & Craufurd, P. (2020). A regional synthesis of seven-year maize yield responses to conservation agriculture technologies in Eastern and Southern Africa. *Agriculture, Ecosystems & Environment*, 295, 106898. https://doi.org/10.1016/j.agee.2020.106898

Nyagumbo, I., Nyamayevu, D., Chipindu, L., Siyeni, D., Dias, D., & Silva, J. V. (2024). Potential contribution of agronomic practices and conservation agriculture towards narrowing smallholders' yield gaps in Southern Africa: lessons from the field. *Experimental Agriculture, 60*, e10. https://doi.org/10.1017/S0014479724000012

Nyamayevu, D., Nyagumbo, I., Chipindu, L., Li, R. Q., & Liang, W. L. (2025). Crop diversification and reduced tillage for improved grain and nutritional yields in rain-fed maize-based cropping systems of semi-arid Malawi. *Experimental Agriculture*, 61, e1. https://doi.org/10.1017/S0014479724000267

Oliveira, E. M., Wittwer, R., Hartmann, M., Keller, T., Buchmann, N., & van der Heijden, M. G. (2024). Effects of conventional, organic and conservation agriculture on soil physical properties, root growth and microbial habitats in a long-term field experiment. *Geoderma*, 447, 116927. https://doi.org/10.1016/j.geoderma.2024.116927

Phiri, A., Njira, K., & Dixon, A. (2024). Comparative effects of legume-based intercropping systems involving pigeon pea and cowpea under deep-bed and conventional tillage systems in Malawi. *Agrosystems, Geosciences & Environment, 7(2)*, e20503. https://doi.org/10.1002/agg2.20503

R Core Team (2023). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

TerAvest, D., Carpenter-Boggs, L., Thierfelder, C., & Reganold, J. P. (2015). Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. *Agriculture, Ecosystems & Environment*, 212, 285-296. https://doi.org/10.1016/j.agee.2015.07.011

Thierfelder, C., Matemba-Mutasa, R., Bunderson, W. T., Mutenje, M., Nyagumbo, I., & Mupangwa, W. (2016). Evaluating manual conservation agriculture systems in southern Africa. *Agriculture, Ecosystems & Environment*, 222, 112-124. https://doi.org/10.1016/j.agee.2016.02.009

Thierfelder, C., & Mhlanga, B. (2022). Short-term yield gains or long-term sustainability?–a synthesis of Conservation Agriculture long-term experiments in Southern Africa. *Agriculture, Ecosystems & Environment*, 326, 107812. https://doi.org/10.1016/j.agee.2021.107812

Tiyeni Malawi (2023) A Field Manual Deep Bed Farming.

Tholo, H. M., Kadewa, W., Chisenga, C., Gondwe, S., Zuza, E.J., Mwase, W., ... & Nyengere, J. (2025). Web-based spatial decision support system for optimum route to forest fires: A case of Viphya plantations. Trees, Forests and People, 19, 100740. https://doi.org/10.1016/j.tfp.2024.100740

Wolka, K., Mulder, J., & Biazin, B. (2018). Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. *Agricultural water management*, 207, 67-79. https://doi.org/10.1016/j.agwat.2018.05.016