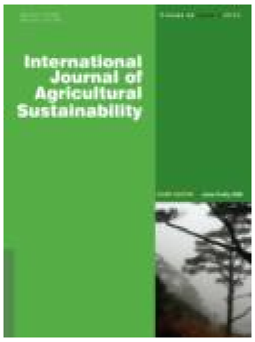

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Assessing on-farm impacts of the deep bed farming system on soil and water conservation, and maize yields among smallholder farmers in Malawi

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ABSTRACT

Malawi's vulnerability to climate change and declining soil fertility underscores the need for climate-smart, soil-conserving agricultural practices. In Malawi, the deep bed farming (DBF) system offers promising solutions for smallholder farmers facing these challenges. This study evaluated the effectiveness of DBF in improving soil and water conservation and maize productivity in Malawi. On-farm assessments and farmer interviews revealed that the DBF reduces soil erosion by over 50% while increasing maize yields by 51% compared with conventional ridge-based (CR) farming. These results showcase the DBF's capability to meet farmers' short-term food security needs while mitigating soil degradation through erosion. DBF also showed consistently greater organic matter, organic carbon and phosphorus contents (19.8%, 22% and 28.7%, respectively), indicating that DBF has the potential to improve and conserve soil fertility in Malawi. The variability in farmers' adherence to essential DBF practices, such as crop residue retention and manure application, indicates a need for a tailored approach to DBF promotion focusing on site-specific suitability and locally driven adaptive learning among farmers. Moreover, caution is necessary when providing input support to avoid dependency and ensure that farmers focus on the core features of DBF.

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Deep bed farming; conservation agriculture; conventional ridge-based; strategic tillage; no-till CA; soil erosion; soil compaction

1 Introduction

Food insecurity among smallholder farmers in sub-Saharan Africa (SSA) continues to pose a significant challenge due to persistently low crop yields. This situation is exacerbated by factors such as declining soil fertility, soil erosion, low input levels, and population growth, which lead to land fragmentation and overuse over time (Vargas & Omuto, 2016). These challenges are further compounded by the increasing frequency and intensity of climate change-induced events, including droughts, dry spells, and heavy rainfall, which devastate crops and cause loss of life and livelihoods across the region, particularly in Malawi (Thierfelder et al., 2017). Projections indicate that climate change will continue to pose serious threats to food security for these resource-poor farmers (IPCC, 2022; Sabola, 2023), highlighting the urgent need to adapt existing farming systems and adopt climate-smart practices. Such practices are essential for replenishing soil fertility, preventing further soil and water degradation, and improving crop productivity (Cairns et al., 2012; Madembo et al., 2020).

Conservation agriculture (CA), characterised by its three core principles of minimum soil tillage, permanent organic soil cover, and crop diversification and rotation (Grabowski & Kerr, 2013), has been extensively promoted in the SSA region as a sustainable agricultural practice (Fisher et al., 2018; Steward et al., 2018). The growing interest in CA stems from its numerous benefits, including increased water infiltration, enhanced soil biodiversity, improved soil structure and fertility, and consistently increased crop yields. Recent studies estimate that by practicing no-till CA, farmers can avoid the release of nearly 300 kg of carbon dioxide equivalents (CO_2e) per hectare per tillage event (Freitag et al., 2024). These benefits accrue over several years, largely due to the consistent retention of crop residues (Giller et al., 2009, 2015; Kassam

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et al., 2009; Thierfelder & Mhlanga, 2022). Additionally, there has been a notable shift in CA practices from reduced tillage to the elimination of tillage, known as no-till CA (Asfaw et al., 2018; Fisher et al., 2018; Thierfelder et al., 2017).

Despite significant financial investments by non-governmental organisations (NGOs), the donor community, government departments, and research institutions to promote CA in SSA countries, its adoption has remained stagnant. The literature indicates dis-adoption among smallholder farmers (Chinseu et al., 2019; Grabowski & Kerr, 2013; Pangapanga-Phiri et al., 2024). Freitag et al. (2024) estimate that approximately 200 million hectares of the total 4.8 billion hectares of cultivated land globally are under some form of CA, representing approximately 4.2%. In Africa, only 1.5 million hectares are managed using some form of CA, representing 1.1% (Kassam et al., 2018), indicating that CA is largely practised among affluent farmers in the global North and South America.

According to CGIAR's 2020 report, CA covers approximately 627,000 hectares in Malawi, Zambia and Zimbabwe combined, accounting for 4.5% of the total 13.7 million hectares of cultivated land in these countries. These figures include farmers involved in sentinel CA sites, which are areas where CA has been consistently promoted, supported, and implemented over an extended period (Pangapanga-Phiri et al., 2024), further complicating the adoption statistics. Despite the apparent benefits of this farming system, the low adoption rates raise concerns about its suitability and applicability among resource-constrained smallholder farmers in countries such as Malawi (Giller et al., 2009, 2015).

The literature indicates that practising no-till without proper mulching can be detrimental due to soil crusting, reduced infiltration, increased evaporation, escalated soil erosion, decreased soil moisture availability, heightened weed infestation and poor crop germination (Anderson et al., 2014; Bouwman et al., 2021; Chinseu et al., 2019). These issues consequently lead to reduced crop yields (Thierfelder, Mombeyarara, et al., 2013), which may also explain the dis-adoption and low CA adoption rates among resource-constrained farmers across SSA (Brown et al., 2017; Chinseu et al., 2019). This situation increases the vulnerability of smallholder farmers to climate change impacts and food insecurity (Giller et al., 2009; Mazvimavi, 2016).

A study by Chinseu et al. (2019) examining the reasons behind farmers in Malawi abandoning CA identified similar challenges, revealing that many farmers are unable or unwilling to maintain CA practices once donor funding, which provides incentives in the form of inputs, is withdrawn. Furthermore, Pedzisa et al. (2015) found that a large number of farmers who adopted CA during the period of active promotion eventually abandoned the practices in the absence of support from NGOs. Similarly, Brown et al. (2017) reported that the low adoption rate of CA in many African countries is attributed to smallholder farmers' negative assessments of CA's suitability and performance, particularly in relation to their resource constraints and immediate food security objectives.

Moreover, the benefits of CA typically materialize after an extended period of consistent practice, usually 5–10 years, making it less attractive for smallholder farmers with immediate food security needs (Giller et al., 2009; Ngwira et al., 2012, 2014). These concerns highlight the challenges related to the suitability and applicability of no-till systems and their 'one-size-fits-all' promotion approach for smallholders in SSA (Andersson et al., 2012; Giller et al., 2009).

In Malawi, the implementation of no-till CA faces challenges arising from the application of no-till practices on soils that have been compacted and degraded owing to years of hand hoe tillage, as illustrated in Figure 1 (Mloza-Banda et al., 2016; Ngwira et al., 2014). Farmers are discouraged from tilling their soils, with the expectation that retaining crop residues will eventually enhance the physical and biochemical properties of the soil (Giller et al., 2015). However, maintaining crop residues in Malawi and neighbouring countries is widely recognized as problematic. This issue is due to factors such as low biomass production, competing uses for these resources, and the trade-offs involved in crop–livestock mixed farming systems (Anderson et al., 2014; Erenstein et al., 2012; Steward et al., 2018).

Conversely, occasional or 'strategic tillage' has demonstrated both environmental and livelihood benefits while addressing farmers' immediate food needs (Giller et al., 2015; Peixoto et al., 2020; Wortmann et al., 2020). In Brazil, Sever (2021) recommended performing one-off strategic tillage every five to ten years to address soil compaction, runoff, and weed infestation on large-scale commercial farms. According to Sever (2021), such tillage reduces weed populations by more than 70%, improves soil physical conditions, enhances nutrient uptake by crops, prevents nutrient stratification, and increases the soil carbon depth.

Figure 1. Soil erosion on a compacted soil under conventional ridge-based system in Malawi (photo by Tiyeni Malawi).

Similarly, Dang et al. (2015) and Peixoto et al. (2020) found that occasional tillage in no-till systems reduces soil bulk density, penetration resistance, soil erosion, and runoff while increasing soil total porosity, microporosity, soil-water infiltration, and microbial biomass carbon (MBC).

In response to widespread soil compaction on smallholder farms and the resulting soil degradation and declining maize yields in Malawi (Shaxson et al., 1997; Snapp, 1998), Tiyeni, a local NGO, has promoted a series of soil and water conservation practices collectively known as DBF since 2005. Although DBF incorporates the principles of permanent organic soil cover, crop rotation, and diversification, it differs from conventional CA systems. Instead of eliminating tillage, DBF advocates for the initial breaking of compacted soils.

Despite nearly two decades of implementation, the impacts of DBF on soil and water conservation and crop productivity remain under-researched in Malawi. Does practising the DBF lead to reduced soil degradation, rainwater conservation and an increase in crop productivity among smallholder farmers in Malawi? This paper investigates the impacts of the DBF on soil and water conservation and maize yields promoted among smallholder farmers in Malawi by Tiyeni. The study addresses the following specific aims:

1. To explore variations in farmers' practices of DBF and their impacts on its effectiveness,
2. To evaluate the effects of DBF on soil and water quality,
3. To assess maize yield responses to variations in soil and water quality, and
4. To examine farmers' understanding of soil and maize yield dynamics based on their DBF experiences.

While we provide some statistical analysis to contextualize our findings and interview results, the primary aim of this research is not to deliver generalisable, controlled experimental outcomes. Instead, we focus on achieving a practical understanding of the impacts of DBF as implemented by smallholder farmers within their unique social-ecological contexts. Given that DBF's principal components include manure application and residue retention, our discussions with farmers and the resulting data in this paper explore how these components interact and influence the observed changes in soil and maize yields.

2 Materials and methods

2.1 Research design and study sites

Our on-farm investigation of the impacts of DBF on soil, water and maize yields utilised a convergent mixed-methods research design (Creswell & Creswell, 2018), underpinned by a social-ecological systems (SES) approach. Unlike conventional approaches that aim to produce widely generalisable results, the SES approach offers a framework for analysing place-specific interactions between people and environmental processes. This allows for the identification of a range of scenarios with potentially different outcomes (McGinnis & Ostrom, 2014; Ostrom, 2009). This approach addresses a recognised gap in the broader CA literature, which calls for more holistic and in situ appraisals of CA's performance (Giller et al., 2015; Nkala, 2012). The implications for site selection are significant, as each farming environment is unique, necessitating the purposive selection of sites based on their perceived social-ecological variations within this study.

The selection of study sites was further guided by the space-for-time substitution approach (Pickett & Likens, 1989), which facilitates the selection of sites based on the duration of their exposure to a particular phenomenon. The literature indicates that the impacts of CA on soil properties take time to manifest, necessitating studies that span more than five years to adequately understand soil quality changes (Corbeels et al., 2014; Thierfelder et al., 2018). Consequently, our study selected three spatially distinct communities with two-year-old plots and three with five-year-old plots, comprising six study sites located in Northern Malawi (Figure 2). Each site exhibits diverse social-ecological characteristics, including variations in topography, rainfall, and soil type, as well as livelihood characteristics and cultural backgrounds (Table 1).

2.2 Measurement of soil and water variables

Soil erosion was measured by establishing plots following the methodologies outlined by Benyamini (2004) and Bunning et al. (2011). The physical barriers and soil deposit collection troughs were constructed around 10 m by 4 m plots. In collaboration with farmers, soil deposits were harvested from the troughs once a month, sun-dried, and weighed using a spring balance during the 2018–2019 cropping year. Unlike other soil erosion estimation techniques, such as the revised universal soil loss equation (RUSLE) and the soil loss estimation model for Southern Africa (SLEMSA) (Hudson, 1981; Kilewe, 1985), this approach empowers farmers with control and knowledge generation, fostering participation, learning and knowledge exchange.

Water infiltration tests were conducted on each plot using a 15 mm diameter infiltration ring (single ring), a digital timer and a 400 mL calibrated container. Three tests were performed on each plot in collaboration with the participating farmers. In April 2019, a team of two technicians from Lunyangwa Research Station in Mzuzu collected soil samples for the analysis of various soil parameters using an auger, following the procedures outlined by Anderson and Ingram (1993).

Two composite soil samples, each weighing 500 g, were collected from each plot, totalling 48 samples. Samples were taken from depths of 0–20 cm (topsoil) and 20–40 cm (subsoil). To create a composite sample for each depth, four random samples were combined with one sample from the centre of the plot (Chilimba et al., 2012; Petersen, 1994). These samples were processed and analysed at Lunyangwa Research Station following standard soil analysis procedures outlined by Mehlich (1984), Anderson and Ingram (1993), Wendt (1996) and Chilimba et al. (2012). The analyses included pH, electrical conductivity (EC), organic matter content (OM), organic carbon (OC), nitrogen (N), available phosphorus (P) and bulk density (BD). The laboratory data were analysed for descriptive statistics and factor analysis (principal component analysis, PCA) using the Statistical Package for the Social Sciences (SPSS) version 27. The Shapiro–Wilk normality test at $p < 0.05$ indicated that some datasets were not normally distributed, necessitating the use of the non-parametric Mann–Whitney U test (Razali & Wah, 2011; Shapiro & Wilk, 1965).

2.3 Maize yield measurement

The entire plots were harvested, and the maize cobs were shelled and dried using the traditional methods in the study areas. Two measurements were taken: (a) weight using a spring balance in kilograms and (b) volume using 20-litre capacity buckets, each typically weighing 20 kg. Both measurements were meticulously documented by the researcher and the farmers, with the latter method being the farmers' preferred technique for measuring yield. The maize yield data were subsequently analysed using SPSS.

2.4 Participatory learning and action methods

Participatory methods such as interviews, group discussions, transect walks and observations were utilised to investigate farmers' knowledge of soil and water dynamics, maize yield, and their experiences with DBF (Chambers, 1997; Chevalier & Buckles, 2019; Denzin & Lincoln, 2011). The group discussion participants

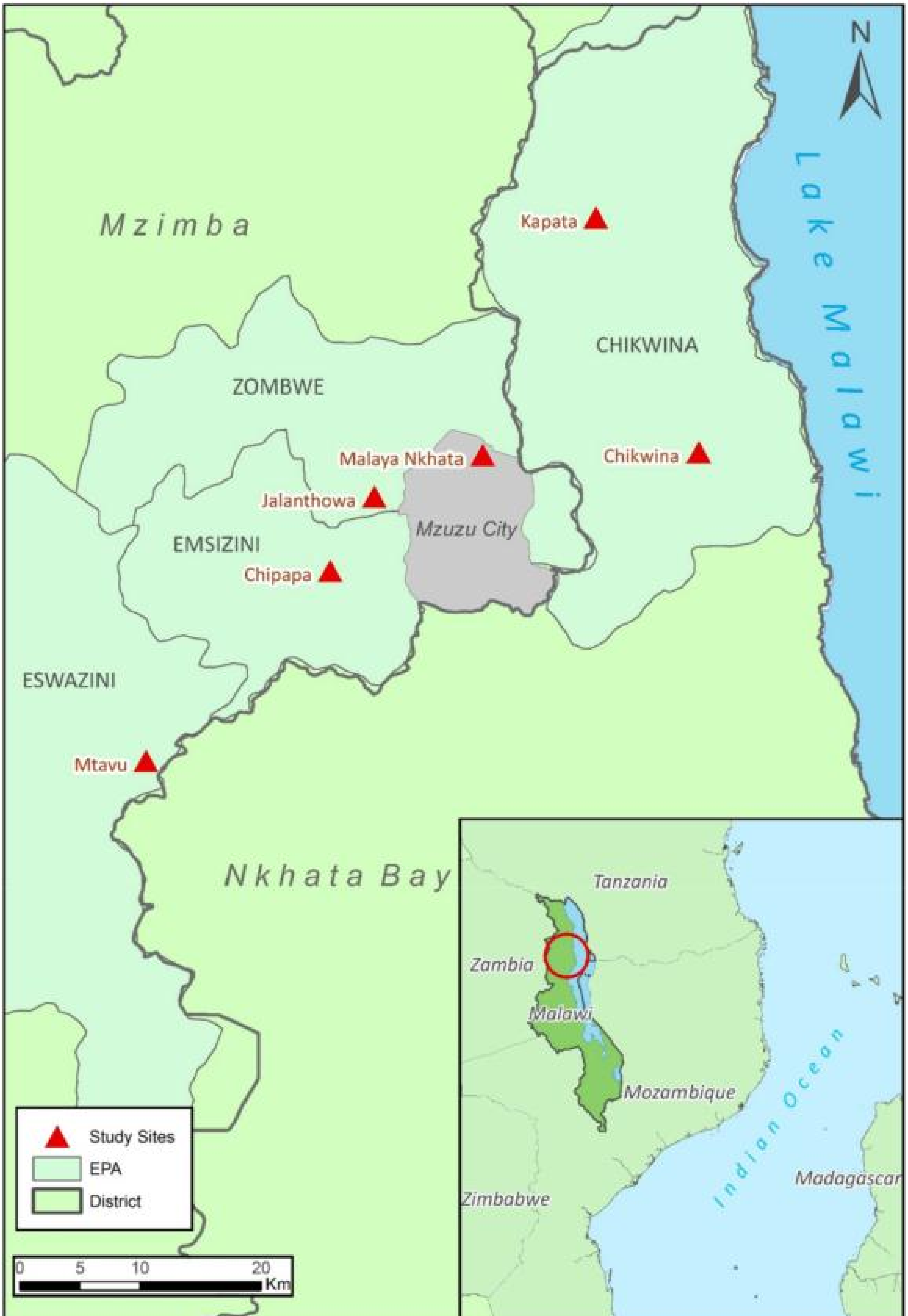

Figure 2. Location of the study sites in northern Malawi.

Table 1. Study sites and their characteristics.

Category	Group	Location	Site description
Two-year-old sites	Mtavu	11°36′12.677″S 33°45′53.013″E	Slightly steep terrain, varied soil characteristics with deep, dark, well-drained, and fertile soils along and in wetlands and shallow, brownish, stony, and poorly drained soil going upland. Rainfall between 700 and 1200 mm/year. Land fragmentation due to high population density.
	Kapata	11°12′01.157″S 34°06′03.539″E	Steep slopes with high-rising mountains with shallow but fertile ferrallitic soils and sparsely distributed loamy clay soil along streams and in wetlands. High rainfall per year (1200–1500 mm/year).
	Malaya Nkhata	11°22′38.464″S 34°00′57.402″E	Flat area with perennial streams forming networks of wetlands with reliable and high rainfall (1200–1500 mm/year). Fertile loamy soils in the wetlands and along streams and infertile sandy soils that are unsuitable for a range of crops upland.
Five-year-old sites	Chikwina	11°22′56.457″S 34°10′05.731″E	Area with very steep slopes and high rainfall (over 1600 mm/year) with shallow and poorly drained soils. Unlike the other sites, Cassava is the staple crop.
	Chipapa	11°28′09.599″S 33°53′59.573″E	Nearly flat area with highly degraded sandy-loam soils with rainfall between 800 and 1000 mm/year.
	Jalanthowa	11°24′35.051″S 33°56′04.746″E	Clayey loamy soils with undulating to nearly flat terrain. Rainfall 800–1200 mm/year. Land fragmentation due to high population density.

included the 12 farmers whose plots were sampled, along with other group members. The qualitative data were transcribed, verified for accuracy, and analysed using NVivo through content and thematic analyses. The qualitative findings are presented alongside quantitative analyses where appropriate.

2.5 The deep bed farming (DBF) method

The DBF practice begins with tillage to a depth of 30 cm to break up soil hardpans, which are compacted layers formed because long-term hand-hoe tillage is typically limited to 15–20 cm (Mloza-Banda et al., 2016; Ngwira et al., 2014; Shaxson et al., 1997; Snapp, 1998). This is followed by 1-meter-wide raised seedbeds aligned with contour ridges at zero gradient, box ridges in the furrows between the beds (Figures 3 and 4), and raised footpaths within furrows (Dixon et al., 2017). Contour ridges are planted with reinforcement grasses such as *Vetiveria zizanioides* (vetiver grass), *Tephrosia vogelii* (tephrosia), or lemongrass (*Cymbopogon citrus*), depending on the area and farmer preference. These grasses provide multiple benefits, including animal fodder, natural pesticides and organic matter.

After the initial deep tillage in the first year, further tillage in the field is discouraged (minimum tillage). Farmers are encouraged to: (a) practice permanent organic soil cover through crop residue retention on bed surfaces; (b) produce and apply manure; and (c) engage in crop rotation and diversification. The production and application of manure are particularly encouraged because of its ability to improve soil fertility and structure, as well as farmers' limited financial capacity to purchase inorganic fertilizers.

3 Results

3.1 Variations in farmers' practice of the DBF

Although crop residue retention is a fundamental component of DBF and other CA practices, field observations, group discussions, and interviews revealed its widespread neglect. This neglect results in de-compacted soil being vulnerable to desiccation due to sun exposure (Figure 5) and unchecked oxidation of soil organic matter, unlike deep beds with crop residues (Figure 6). Additionally, bare deep beds expose the de-compacted soil particles to direct raindrop impact, leading to surface sealing and splash erosion, among other issues.

Observations indicated that most farmers' fields do not adhere to the recommended tillage depth of 30 cm prior to bed construction, resulting in shallow tillage depths similar to those in adjacent conventional ridge (CR) plots. Another overlooked aspect of the DBF system was the creation of raised footpaths, which were intended to prevent walking directly on the deep beds and re-compacting the soils during various farming tasks. Consequently, many beds displayed signs of human footprints. Additionally, goats, pigs, and cattle were allowed to roam freely across farms, further trampling the de-compacted soils on both DBF and CR plots.

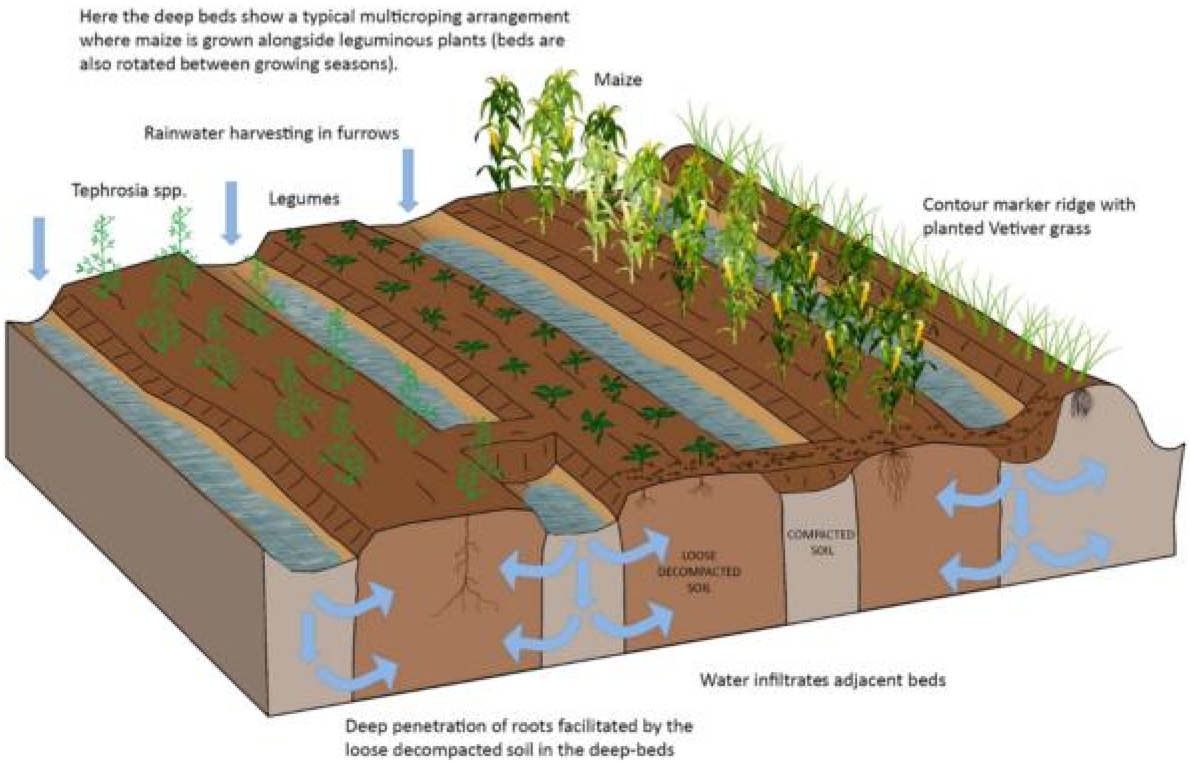

Figure 3. Conceptual model of the deep DBF (Dixon et al., 2017).

Figure 4. Box ridges in a one-year DBF field (photo by Godfrey Kumwenda).

Group discussions revealed that the primary reasons for shallow tillage and the absence of raised footpaths were the difficulties of digging to the required depth and the scarcity of labour. Interviews also indicated that livestock typically roamed without restrictions during the summer due to the lack of formal rules limiting their movement.

Manure application was found to be inconsistent or absent across all the study sites. Group discussions revealed that the primary reasons for this inconsistency are the additional labour required for producing, transporting, and applying manure. Additionally, farmers cited the lack of sufficient livestock to produce the necessary amount of manure as a significant contributing factor.

Figure 5. Bare and re-compacted deep beds in Chipapa.

Figure 6. Deep beds fully covered with crop residues in Mtavu.

3.2 Soil erosion

The results indicate that the DBF significantly reduces soil erosion by 50% and 47.6% in the first two and five years of implementation, respectively, relative to CR ($p = 0.004$), as shown in Tables 2 and 3. An analysis of data from two- and five-year DBF plots revealed a significant increase in soil erosion over time ($p = 0.020$), as noted in Table 4. Similarly, soil erosion was markedly greater in the five-year CR plots compared to the two-year DBF plots ($p = 0.020$). No significant differences were observed when comparing the two- and five-year CR plots ($p = 1.0$) or when comparing the combined two-year plots with all five-year plots ($p = 0.774$). Overall, the DBF plots consistently exhibited lower soil erosion rates than the adjacent CR plots (Figure 7).

Table 2. Summary of two- and five-year soil variables and maize yields ($n = 48$).

		2 year plots			5 year plots		
Variables		Mean	Standard deviation	% Change	Mean	Standard deviation	% Change
EC (dS/m)	CR	11	6	36.4	9	3	33.3
	DBF	15	7		12	5	
pH	CR	5.78	0.80	0	5.70	0.37	−2.1
	DBF	5.78	0.60		5.58	0.47	
P (ug/g)	CR	26.04	19.18	13.1	22.42	17.08	40.4
	DBF	29.45	18.58		31.47	17.31	
OC (%)	CR	0.39	0.23	56.4	0.56	0.22	5.4
	DBF	0.61	0.27		0.59	0.28	
OM (%)	CR	0.68	0.39	54.4	1.02	0.44	0
	DBF	1.05	0.47		1.02	0.49	
N (%)	CR	0.03	0.02	66.7	0.05	0.03	0
	DBF	0.05	0.02		0.05	0.02	
BD (ug/g)	CR	0.64	0.67	0	0.68	0.71	−1.5
	DBF	0.64	0.68		0.67	0.70	
Soil erosion (t/ha)	CR	1.6	0.6	-50	2.1	1.5	−47.6
	DBF	0.8	0.4		1.1	0.6	
Infiltration rate (mm/hr)	CR	10352.5	9223.6	101	14972.5	10498.8	36.4
	DBF	20808	14289.3		20420	12305	
Maize yields (t/ha)	CR	4.75	3.6	51.6	3.9	1.9	25.6
	DBF	7.2	4.7		4.9	1.4	

EC = electrical conductivity; P = phosphorus, OC = organic carbon, OM = organic matter, N = nitrogen, BD = bulk density.

Table 3. Differences between DBF and CR using Mann–Whitney U test at $p < 0.05$ ($n = 24$).

Variable	Z-score	Sig. ($p < 0.05$)	Mean		% Change
pH	−0.216	0.825	DBF	5.68	−1.0
			CR	5.74	
EC (dS/m)	2.226	**0.025**	DBF	13.70	39.4
			CR	9.83	
P (ug/g)	1.453	0.147	DBF	31.21	28.7
			CR	24.25	
OC (%)	1.34	0.18	DBF	0.61	22
			CR	0.50	
OM (%)	1.185	0.234	DBF	1.03	19.8
			CR	0.86	
N (%)	1.453	0.147	DBF	0.05	25
			CR	0.04	
BD	−0.202	0.841	DBF	1.30	−0.8
			CR	1.31	
Infiltration rate (mm/hr)	−1.502	0.072	DBF	20614.2	62.8
			CR	12662.5	
Maize yields (t/ha)	1.096	0.271	DBF	6.0	39.5
			CR	4.3	
Soil erosion (t/ha)	−2.605	**0.004**	DBF	0.9	−50
			CR	1.8	

EC = electrical conductivity; P = phosphorus, OC = organic carbon, OM = organic matter, N = nitrogen, BD = bulk density.

Table 4. Comparison of soil variables in 2- and 5-year DBF and CR plots (p-values).

Variable	$DBF_{2\,yr} - CR_{2\,yr}$	$DBF_{5\,yr} - CR_{5\,yr}$	$DBF_{2yr\text{-}5yr}$	$CR_{2yr\text{-}5yr}$	$DBF_{2\,yr} - CR_{5\,yr}$	2 yr–5 yr
pH	0.794	0.453	0.509	0.703	0.904	0.797
EC	0.141	0.078	0.312	0.238	0.013	0.123
P	0.522	0.118	0.689	0.703	0.471	0.893
OC	**0.043**	0.952	0.976	0.173	0.904	0.522
OM	**0.043**	0.952	0.841	0.173	0.904	0.433
N	**0.040**	0.888	0.748	0.204	0.689	0.421
BD	0.631	0.337	0.631	0.337	0.337	0.651
Infiltration rate	0.378	0.262	0.936	0.471	0.471	0.843
Maize yields	0.005	0.015	**0.045**	0.714	**0.030**	0.692
Eroded soil	0.065	0.065	**0.020**	1.00	**0.020**	0.774

EC = electrical conductivity; P = phosphorus, OC = organic carbon, OM = organic matter, N = nitrogen, BD = bulk density.

The highest and lowest soil erosion were recorded in Chikwina and Malaya Nkhata, respectively. In Chikwina, the DBF plot recorded 4.5 t/ha of eroded soil compared to 11 t/ha in the adjacent CR plot. This finding indicates that even in a very steep area such as Chikwina, the DBF system was able to reduce soil erosion by 59% compared to the adjacent CR system. Conversely, in Malaya Nkhata, soil erosion was

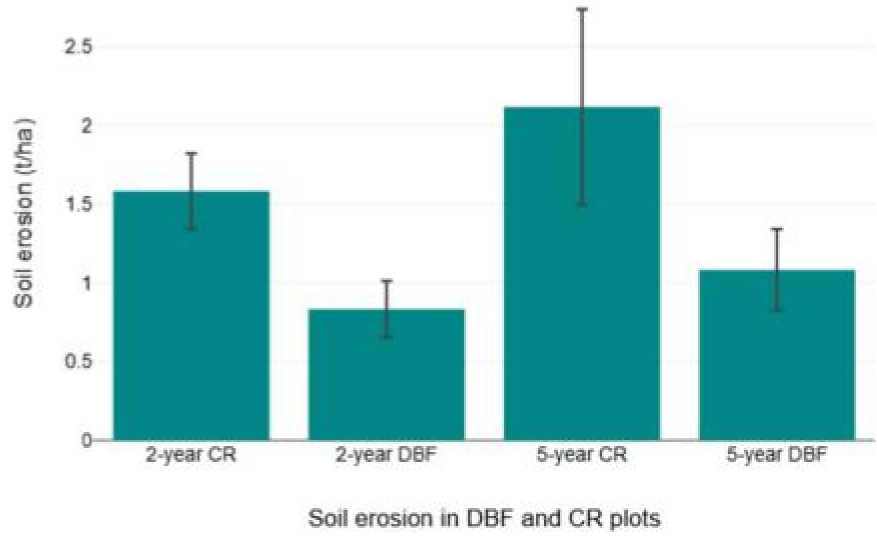

Figure 7. Soil erosion variations in DBF and CR plots (2 yr = 2-year and 5 yr = 5-year).

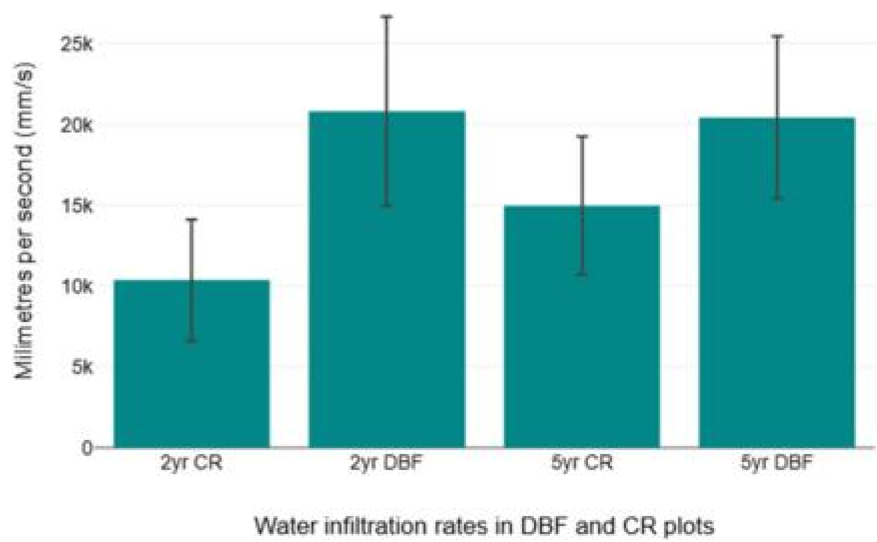

Figure 8. Water infiltration variations in DBF and CR plots (2 yr = 2-year and 5 yr = 5-year).

minimal, with DBF and CR plots recording 1.5 and 2 t/ha, respectively, due to differences in topography and soil types.

3.3 Water infiltration rates

It was anticipated that water infiltration in DBF plots would be greater than that in CR plots due to deep tillage and other interventions. Our results suggest that there were no significant differences between the two farming systems, although DBF consistently presented relatively high infiltration rates, with a p-value of 0.072 (Table 3). In all the cases, the two- and five-year DBF plots presented higher water infiltration rates than the CR plots (Figure 8), indicating reduced soil compaction despite the re-compaction issues noted earlier. Comparisons between the two-year DBF and CR plots, as well as between the five-year DBF and CR plots, were statistically insignificant ($p = 0.378$ and 0.262, respectively) (Table 4). However, the infiltration rate in DBF was 101% higher than that in CR despite being statistically insignificant, possibly reflecting the high variability across plots.

3.4 Soil bulk density (BD)

Despite the expectation that BD values would be significantly lower in DBF due to the initial 30 cm deep tillage in the first year, no significant difference was observed compared to CR ($p = 0.841$) (Tables 3 and 4). The mean BD values were 1.30 mg/m^3 for DBF and 1.31 mg/m^3 for CR, showing little variation between the farming systems and between the two- and five-year plots (Figure 9). However, DBF showed 0.8% lower BD relative to CR, indicating slight impact on soil compaction.

3.5 Phosphorus (P), organic carbon (OC) and organic matter (OM)

However, no significant differences in P concentrations were observed between DBF and CR (Table 3), and higher P levels were nonetheless noted in both the two- and five-year DBF plots compared to CR plots (Figure 10). More than 75% of the P readings in the DBF plots were above or near 20 µg/g, while CR plots retained about 15 µg/g. According to Table 2, no significant differences were found in OC, OM, and N between DBF and CR, with *p*-values of 0.18, 0.234 and 0.147, respectively. However, Table 3 shows

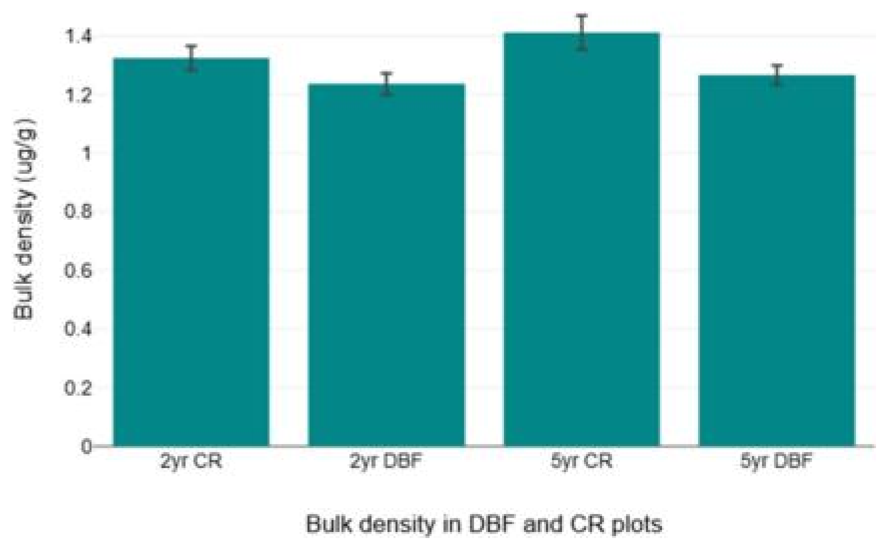

Figure 9. Variations in BD in DBF and CR plots (2 yr = 2-year and 5 yr = 5-year).

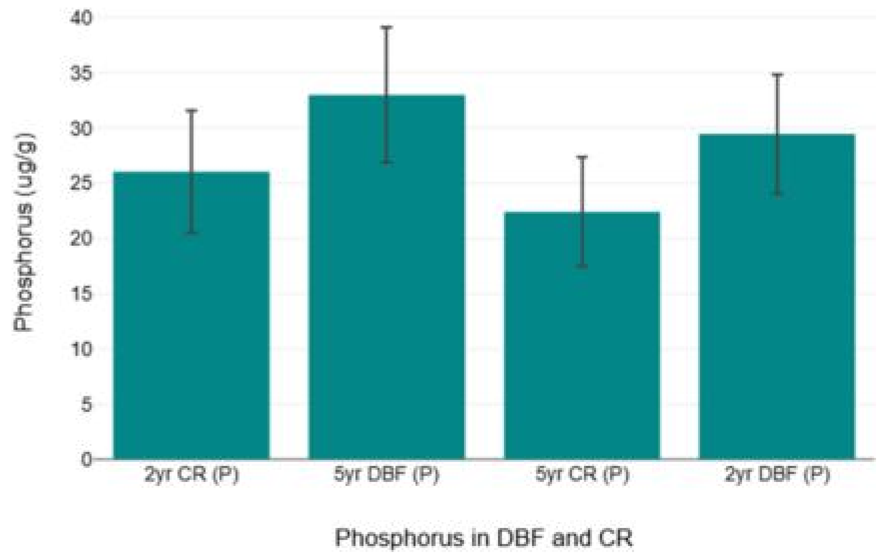

Figure 10. Variations in P levels in DBF and CR plots (2 yr = 2-year and 5 yr = 5-year).

significant differences in OC and OM between two-year DBF and CR plots, with the former retaining higher levels than the latter, while N levels remained consistently low across both farming systems (Figure 11). Furthermore, DBF showed 22%, 19.8% and 28.7% higher OC, OM and P levels compared to CR, indicating improved soil fertility under DBF.

3.6 Soil pH and electrical conductivity (EC)

Since manure application is a key component of DBF, pH levels are expected to be significantly higher in DBF plots compared to CR, but the results showed a 1% decrease in pH in DBF compared to CR plots (Table 3). However, no significant difference was observed ($p = 0.825$) (Table 3). Conversely, the comparison of EC between the DBF and CR plots revealed significantly greater salt contents in DBF ($p = 0.025$) (Table 4). The DBF showed 39.4% greater EC content than CR. The mean EC values were 15 and 12 dS/m for the two- and five-year DBF plots, respectively, while CR plots showed lower EC readings of 11 and 9 dS/m for the same duration.

3.7 Maize yields

Maize yields were significantly greater in the two-year DBF plots compared to five-year CR plots ($p = 0.030$) (Table 4). Similarly, the maize yields in the two-year DBF plots were significantly greater than those in the five-year DBF plots ($p = 0.045$). While not statistically significant, five-year DBF plots presented higher yields than five-year CR plots did ($p = 0.054$) (Tables 2 and 4). Comparing all DBF plots to all CR plots showed no significant differences ($p = 0.271$). Overall, maize yields were consistently greater in DBF (39.5%) than in CR (Table 3 and Figure 12). The highest yields for all plots compared were observed under DBF, with values greater than 13 t/ha while the lowest yields were observed under CR, with values of approximately 1 t/ha.

3.8 Relationships among variables: principal component analysis (PCA)

The nine soil variables and maize yield data were analysed using principal component analysis (PCA) with orthogonal Varimax rotation (Field, 2009; Starkweather, 2011) to condense the data into interpretable factor loadings and identify the variables accounting for the observed changes. Initially, the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity (χ^2) were employed to assess the dataset's suitability for PCA (Field, 2009). Both tests yielded results above the recommended thresholds, with a KMO of 0.609 (>0.5) and a Bartlett's χ^2 of 559.00, indicating that the dataset was adequate for PCA.

By applying Kaiser's criterion, which considers only eigenvalues ≥ 1, three principal components (PCs) were extracted from the dataset, collectively accounting for more than 73% of the variance (Table 5). Initial inspection of the scree plot of the resultant eigenvalues and factor loadings indicated ambiguities, with two inflexions suggesting the existence of four PCs. However, the Orthogonal Varimax rotation (Table 6) and a

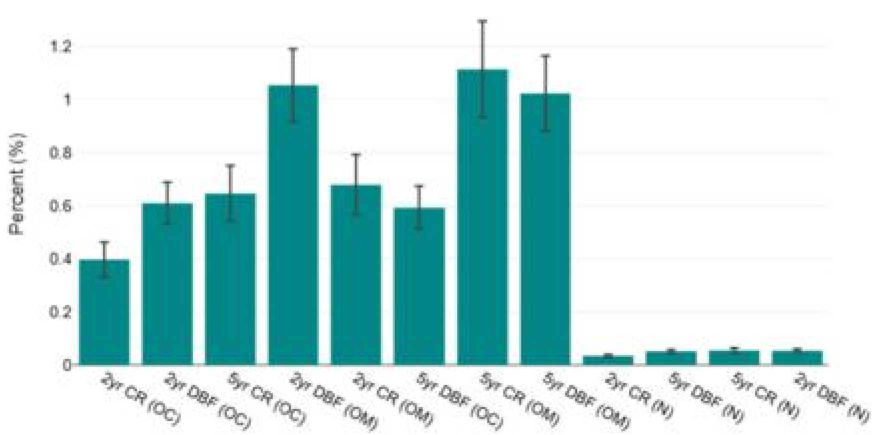

Figure 11. Variations in P, OC and OM in DBF and CR plots (2 yr = 2-year and 5 yr = 5-year).

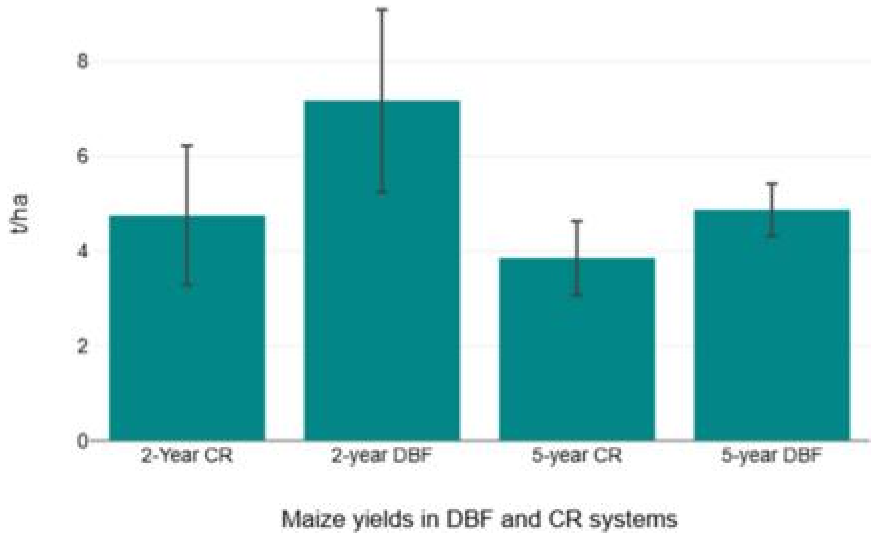

Figure 12. Maize yields in DBF and CR plots (2 yr = 2-year and 5 yr = 5-year).

Table 5. Factor loadings matrix before Varimax rotation.

	Component		
Variables	1	2	3
pH	−0.033	−0.140	0.629
Electric conductivity	0.079	−0.022	0.257
Phosphorus	−0.114	−0.008	0.528
Organic carbon	0.333	−0.019	−0.079
Organic matter	0.337	−0.035	−0.060
Nitrogen	0.330	−0.046	−0.040
Bulk density	−0.047	0.330	0.021
Soil erosion	−0.068	0.300	−0.021
Infiltration rate	−0.002	0.335	−0.197
Maize yields	0.006	0.262	0.038
Eigenvalues	3.095	2.822	1.470
Percent (%) of variance	30.947	28.217	14.696
Cumulative	30.947	59.164	73.860

Extraction method: Principal component analysis. Rotation method: Varimax with Kaiser normalization. Rotations in five iterations.

Table 6. Varimax rotated factor loadings matrix.

	Component		
Variables	1	2	3
Organic matter	0.982		
Organic carbon	0.971		
Nitrogen	0.966		
Bulk density		0.912	
Infiltration rate		0.819	
Soil erosion		0.785	
Maize yields		0.769	
pH			0.816
Phosphorus			0.702
Electric conductivity			0.411

plot of rotated eigenvalues (Figure 13) supported retaining only three PCs, yielding interpretable results with factor loadings > 0.3 after rotation (Andrews & Carroll, 2001; Field, 2009; Starkweather, 2011).

As illustrated in Tables 5 and 6 and Figure 13, OC, OM and N presented the highest loadings on Principal Component 1 (PC1), accounting for more than 30% of the variance. This emphasizes the capacity of farmers to retain and restore nutrients through the DBF system. Given its critical role in fostering a sustainable soil ecosystem, OM is particularly significant under PC1 (Shaxson et al., 2014). These three parameters showed a strong correlation, with Pearson's *r* coefficient approaching 1 (Table 6). PC2 encompasses soil bulk density, water infiltration rates, soil erosion quantities, and maize yields, explaining more than 28.21% of the

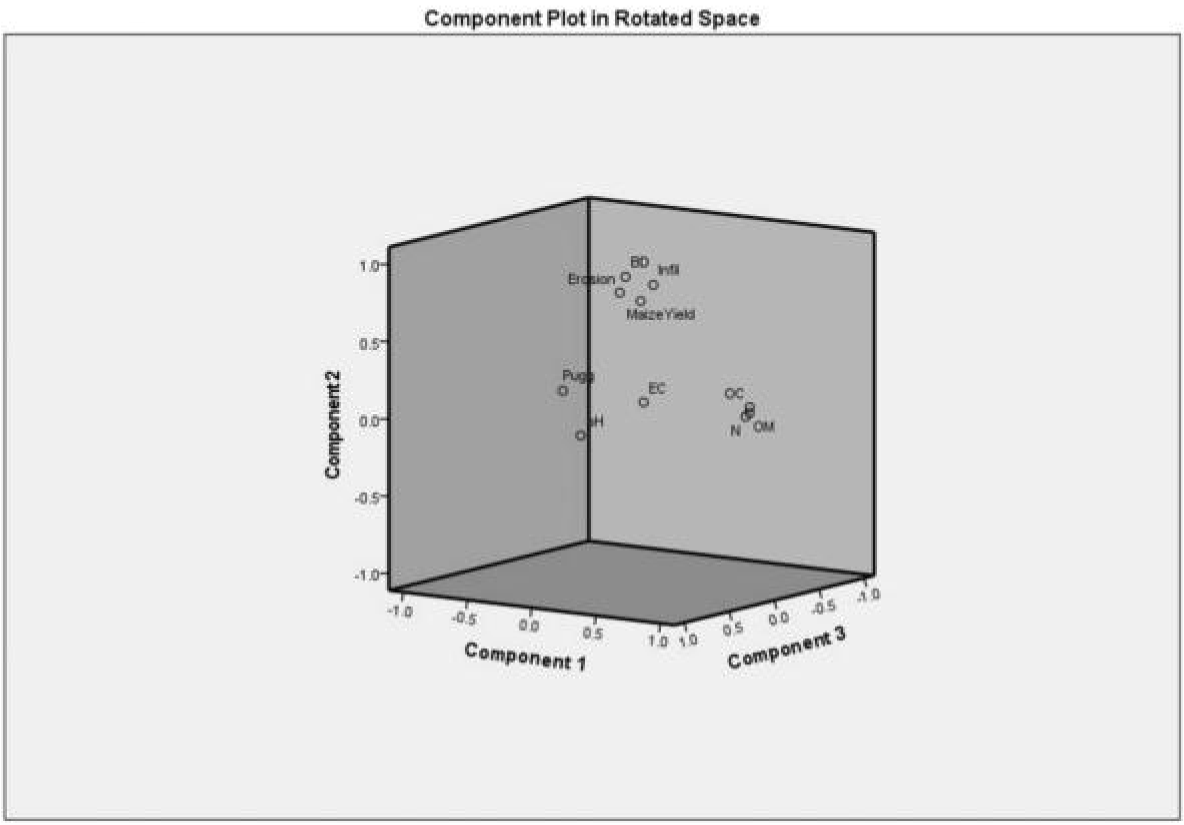

Figure 13. The three principal components in rotated space.

variation. This component represents the physical aspects of soils under the DBF system and their relationship to maize yields. With a coefficient exceeding 0.7 (Table 5), these four parameters demonstrated a strong interrelation.

PC3 consists of pH, P, and EC, which represent soil chemical parameters and account for 14.69% of the variance. Although these elements are crucial for crop growth, they do not exhibit a strong correlation with maize yields, as observed with PC1. Consequently, elements of PC1 (OC, OM and N) and PC2 (BD, infiltration rates and soil erosion), along with their combinations and interactions, are the primary contributors to the performance of DBF. By reducing soil erosion to half that of CR and alleviating soil compaction, DBF provides immediate benefits, including improved rainwater harvesting and infiltration, moisture conservation and decreased soil degradation. These advantages lead to enhanced crop productivity from the first year of implementation.

4. Discussion

While uniformity in DBF practices has been widely advocated to ensure maximum benefits, this study has shown that DBF is implemented in diverse ways by different farmers. The variations in DBF practices are influenced by a range of socio-ecological factors, including environmental conditions, labour constraints, and the absence of restrictions on animal movement. For instance, farmers who did not perceive soil erosion as a significant issue on their land viewed the implementation of contour and box ridges or the retention of crop residues as unnecessary labour. These findings align with widely cited challenges that prevent farmers from fully engaging in all three CA practices (Bouwman et al., 2021; Giller et al., 2009). Consequently, these findings underscore the importance of an adaptive approach to promoting DBF and other CA practices (Ndah et al., 2018). Lee and Gambiza (2022) and Giller et al. (2009) have noted that the success of CA in SSA countries hinges on how well these systems meet the needs of farmers. Thus, the effectiveness and sustainability of DBF are dependent on site-specific considerations during its promotion.

Our findings indicate that DBF significantly reduces soil erosion by more than 50% compared to CR farming systems. These results align with those of Peixoto et al. (2020), who reported that occasional tillage reduces soil erosion by de-compacting soils, leading to improved soil-water infiltration and reduced runoff. The northern region of Malawi typically loses between 0.4 and 39 t/ha of soil per year due to erosion, resulting in the widespread loss of fertile topsoil essential for crop production (Nakhumwa, 2004; Ngwira et al., 2014; Vargas & Omuto, 2016). Sustaining these benefits depends on farmers' willingness and ability to implement essential DBF practices, such as crop residue retention and manure application, to protect de-compacted soils and improve soil fertility. Consistent with Peixoto et al. (2020), Schlegel et al. (2020) and Sever (2021), this paper demonstrates that strategic tillage through the DBF system significantly enhances soil water infiltration. In the face of increasing droughts and heavy rainfall events in Malawi (Steward et al., 2018; Thierfelder et al., 2017), improved rainwater infiltration is crucial for maximising the utilisation of available rainfall by crops while minimising flash floods, surface runoff, and soil erosion. Given the high susceptibility of maize-based rainfed agriculture to climate variability and change (Porter et al., 2014; Steward et al., 2018), the benefits of DBF are vital in bolstering agricultural resilience and sustainability in Malawi and across sub-Saharan Africa.

Interviews with farmers also revealed that the increased water infiltration benefits of the DBF are widely observed and acknowledged among farmers with most of participants frequently mentioning the water harvesting and infiltration in DBF. For instance, Participant 4MPJ noted that

> '*Water is trapped in box ridges while the plot remains closed. This makes sure that the water does not go outside the plot. The tilled soil made into substantive 1m wide beds makes it easy for a large volume of rainwater to infiltrate compared to compacted small ridges. This is why maize on DBF does not wilt like on ridges when there is a dry spell.*'

DBF plots consistently showed lower BD values than the typical reported range of 1.41–1.50 mg/m^3 for 0–30 cm depths in Malawi (Douglas et al., 1999). Soil compaction with BD values greater than 1.6 mg/m^3 is associated with reduced soil porosity, poor rainwater infiltration, increased runoff and soil erosion, and restricted root growth, all of which negatively impact crop productivity (Njoloma et al., 2016; Shaxson et al., 2014). Factors such as the lack of permanent cover or crop residue retention, physical trampling of bed surfaces, and exposure to raindrop impacts may contribute to the observed soil bulk density in DBF plots.

Farmers widely recognise that incorporating crop residues, especially on newly constructed beds, is normally neglected, with the assumption that this can start in the second year of practising the DBF. Furthermore, the continuation of crop residue retention even when a farmer starts this practice has been found to be inconsistent and problematic. For instance, Participant 4DMJ said

> '*Many of us did not lay maize stalks on deep beds in the first year. They were all destroyed or used elsewhere by the time we realised beds needed them too. My plan was to start mulching in year two onwards.*'

Consistent and adequate availability of crop residues on DBF can significantly amplify these benefits among DBF farmers and help them to effectively adapt to the increasing risk of crop failure due to the impacts of climate change on rainfall amounts and patterns across Malawi.

While manure application is essential for improving crop yields and soil fertility, the implementation of this practice also faces various challenges. These include labour trade-offs where farmers compete for their time, making difficult decisions as to whether to make and apply manure or use the same time and labour for other income-generating activities, such as irrigation farming, among other essential livelihood activities. In addition, there is a lack of raw materials, especially livestock, to provide essential animal manure for the production of various types of manure. For example, Participant 2LC noted that

> '*others fear making manure because it's a thing we are not used to doing. It's an additional task. Furthermore, others do not have livestock for manure. Deep beds need manure*'.

Our findings indicate that DBF plots consistently presented higher P levels compared to adjacent CR plots. This is consistent with observations by Mloza-Banda et al. (2016) and Njoloma et al. (2016), who also found slightly higher P levels in no-till systems than in the CR. Conversely, OC and OM were lower than the optimal levels (0.8%–2%) for maize production in both farming systems (Snapp, 1998). These findings likely reflect the diverse DBF practices among smallholder farmers, including crop residue retention and manure application. Similar studies (Mloza-Banda et al., 2016; Ngwira et al., 2012) reported higher levels of OC, OM and N in no-till CA, attributed to the elimination of tillage, which reduces OC oxidation. The insufficient crop residue retention and inconsistent manure application to smallholder farmer fields may explain the lower-than-expected OC and OM levels under DBF. Nevertheless, the consistent observed increases in OC, OM and P contents under DBF indicate the potential of the DBF to increase soil fertility and nutrient retention over time. Given the wide-spread soil degradation in Malawi, increased adoption and scaling of the DBF among smallholder farmers can significantly reverse this soil degradation and contribute to improved crop productivity.

Our findings indicate that the soil pH in both DBF and CR systems remains below the optimal range of 6.1–7.3 for maize production (The et al., 2006), which is consistent with the slightly acidic nature of tropical African soils (Brewbaker et al., 1985; Granados et al., 1993). The 30 cm deep tillage in the DBF system did not significantly alter the soil pH dynamics. Despite having significantly greater electrical conductivity than the CR plots did, the salt content under DBF remained within the acceptable threshold for optimal maize growth. According to Mloza-Banda et al. (2016) and Abrol et al. (1988), maize thrives in soils with a salt content between 0 and 18 dS/m.

The DBF system has been shown to increase maize yields from the first year of implementation, which contrasts with the results observed in no-till systems. This improvement is crucial for balancing the long-term benefits of CA with farmers' immediate food security needs. Although Schlegel et al. (2020) and Wortmann et al. (2020) did not report significant yield increases after occasional tillage in no-till systems, they noted that tillage for soil compaction, weed management, and nutrient stratification did not adversely affect yields. The primary cause of declining crop productivity on smallholder cultivated land in SSA is the physical degradation of the soil (Corbeels et al., 2014; Thierfelder, Chisui, et al., 2013). While other factors also play a role, soil de-compaction through strategic 30cm tillage in DBF has the most significant impact on improving soil physical conditions and enhancing maize yields, as demonstrated by the PCA results.

Interviews and group discussions with farmers confirmed such findings, where participants widely cited high crop yields, often double or triple the yields in CR, as the main reason for deciding to practice DBF. For instance, Participant 4RMJ noted

> *'I had a plot with very poor soils due to erosion. Maize yields had always have been poor since 10 years ago and ago, so I decided to have deep beds on that land. Now, this plot is my best plot. It's where I get the highest yields, despite it being small in size. Apart from manure and deep tillage, these beds have helped to keep the moisture on that plot and reduced erosion.'*

This signifies how pronounced the yield benefit of the DBF is among farmers. Where adequate and consistent retention and application of crop residue retention and manure respectively are encouraged and practised, the DBF can potentially contribute to the elimination of chronic food shortages among these resource-constrained farmers while helping to restore and conserve degraded soils.

However, the increase in maize yields is less pronounced in five-year DBF plots, likely due to inconsistent crop residue retention and manure application, which are essential DBF practices. The results presented above show 25% higher maize yields under DBF than in CR after five years compared to over 51% increase in maize yields when two-year DBF and CR plots were compared. This inconsistency may stem from farmers' decreasing interest, potentially due to a lack of adaptation to their specific socioecological conditions or a decline in enthusiasm after the cessation of active promotion and support (Anderson et al., 2014; Giller et al., 2009).

5 Conclusion and recommendations

This paper has demonstrated that the DBF system offers numerous advantages, including enhanced rainwater harvesting and infiltration, reduced runoff and soil erosion, and increased water availability for crops. Consequently, farmers can achieve high maize yields rapidly, effectively closing the yield gap common in other CA systems. Tailored promotion of DBF among smallholder farmers in Malawi is crucial for mitigating food insecurity, halting soil degradation, improving soil fertility, conserving soil water, and enhancing the overall resilience of farming systems to climate change impacts. An adaptive and customized approach to DBF promotion and farmer training should be an integral part of the DBF system.

Sustaining the benefits of DBF in both the short and long term depends on farmers' commitment to practices such as crop residue retention, manure application from the first year of DBF practice, preventing soil trampling by humans and livestock, practicing crop rotation, and adhering to other essential features of the system. This may require an adaptive approach to DBF promotion, participatory extension methods, and peer-to-peer learning to help farmers understand the benefits of various DBF components. However, providing input support in promotion programs may risk creating dependency among smallholders, distracting them from focusing on the core features and benefits of the DBF system. The cessation of such support could compromise farmers' willingness to sustain DBF practices. Therefore, caution is necessary when promoting DBF alongside the provision of free inputs to ensure that the latter does not overshadow the former's importance.

6 Further research

Further research is needed to comprehensively understand and quantify the impacts of various DBF features on soil fertility, conservation, and crop productivity. This includes evaluating the quantity and frequency of crop residue retention and manure application, tillage depth, box ridges, and agroforestry components in DBF fields. These studies provide valuable insights into the effectiveness of DBF under diverse social-ecological conditions. While this study was based on a limited number of spatially dispersed plots, the findings offer valuable initial insights into the potential of the DBF to improve soil fertility and crop performance. The observed trends, though drawn from a modest dataset, highlight promising directions for sustainable land management through the DBF. Future research involving larger sample sizes, multi-seasonal trials, and more spatially intensive sampling would help validate and expand upon these results, ensuring broader applicability across diverse agroecological zones in Malawi. Additionally, further investigation is necessary in highly degraded farmlands to assess the potential of DBF in regenerating such lands and its consequent impact on groundwater recharge and nearby streams or wetlands.

Author contributions

Albert Mvula: Conceptualization, methodology, data curation, writing original draft and review and editing, software. Alan Dixon: Conceptualization, funding acquisition, supervision, project administration, review and editing. Ian Maddock: Supervision, software, review and editing.

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