Experimental Agriculture (2025), vol. 61, e1, 1–15
doi:10.1017/S0014479724000267

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Crop diversification and reduced tillage for improved grain and nutritional yields in rain-fed maize-based cropping systems of semi-arid Malawi

Donald Nyamayevu[1,2], Isaiah Nyagumbo[2], Lovemore Chipindu[2], Rui-qi Li[1] and Wei-li Liang[1]

[1]College of Agronomy, Hebei Agriculture University, Baoding, Hebei, China and [2]International Maize and Wheat Improvement Center (CIMMYT), Harare, Zimbabwe
Corresponding author: Donald Nyamayevu; Email: dnyamayevu@gmail.com

(Received 21 December 2023; revised 25 July 2024; accepted 29 November 2024)

Summary

Conservation agriculture (CA), as a key component of sustainable intensification, has been widely promoted across sub-Saharan Africa (SSA) to address low crop productivity. However, the focus has mainly been on improving cereal grain yields, with less focus to its impact on nutritional outcomes. This study sought to assess the productivity potential of CA crop diversification systems and associated crop establishment techniques in terms of grain, protein, and energy yields. An on-station trial was implemented in Malawi for four cropping seasons (2014/15 to 2017/18). Four crop establishment techniques (ridge and furrow, jab planter, dibble sticks, and CA basins) were tested, while cropping systems included conventional cropping system (Conv), CA sole cropping (CaSole), CA intercropping (CA-intercropping), and CA rotations (CA-rotation). In 2014/15 and 2015/16 cropping seasons, characterised by medium and low rainfall, respectively, planting basins and ridge-furrow systems produced higher maize yields compared to jab planter and dibble stick systems. In 2015/16, big and small basins yielded 5061 and 3969 kg ha^{-1}, while jab planter and dibble stick yielded 3476 and 3213 kg ha^{-1}. When there was high and persistent rainfall (2016/17 and 2017/18), direct seeding (jab planter and dibble stick) outperformed basins and ridge-furrow systems. Therefore, the choice of planting basin sizes and whether or not to use dibble stick and jab planter needs to be guided by location or site-specific seasonal forecasts for best results. Grain yield in maize-legume rotation systems consistently outperformed other systems, with maize-groundnut rotations surpassing maize-cowpea intercrops by 987–2700 kg ha^{-1} over four cropping seasons. In intercropping systems, maize-pigeon pea outperformed maize-cowpea by 4–45% during the same period, while maize-cowpea rotation consistently out yielded maize-cowpea intercropping. Intercropping systems, however, provided substantial protein benefits, with maize-pigeon yielding +9.5% (2015/2016), +29.1% (2016/2017) over CA sole, and +2.2% (2017/2018) over cowpea intercropping. Sole systems (conventional and CA sole) yielded the highest caloric energy, while maize-cowpea rotation consistently reduced energy yield by 35% to 54% compared to the highest-yielding systems. Overall intercropping systems can outperform rotation systems in nutritional security but when focus is on maize grain yield alone, intercropping may reduce maize yield when compared to both cereal sole and maize-legume rotation systems.

Keywords: crop rotation; intercropping; protein yield; energy yield; crop establishment techniques

Introduction

In sub-Saharan Africa (SSA), rain-fed systems dominate agricultural production, accounting for more than 95% of the total cropland under staple food production and serving an approximate

41% of the region's population (Mupangwa *et al.*, 2016; Mwansa *et al.*, 2017). On the other hand, the region is characterised by erratic rainfall (Yengoh *et al.*, 2010). Rainfall anomalies often lead to water stress and low crop yields, resulting in widespread poverty, food insecurity, and malnutrition (Makate *et al.*, 2018; Mugiyo *et al.*, 2018). Over the past years, yields for staple food crops such as maize have typically remained low, ranging from 1500 to 2000 kg ha^{-1} (Ligowe *et al.*, 2017; Nyagumbo *et al.*, 2020). More so, changes in crop yield are projected to decline from +3.3% per annum (1987–2007) to +2.4% and +1.9% per annum during 2007–2030 and 2030–2050, respectively (Alexandratos and Bruinsma, 2012). This poses a significant threat to the attainment of Sustainable Development Goals (SDGs) such as Zero Hunger (SDG2) particularly in developing countries (Aryal *et al.*, 2022). Reversing these negative scenarios requires the identification of new or existing agronomic innovations and practices that will close the yield gap and sustainably improve agricultural productivity.

Conservation agriculture (CA) has gained significant attention as a potential sustainable agricultural intensification technology (TerAvest *et al.*, 2015; Mupangwa *et al.*, 2021). Its principles hinge on minimising soil disturbance, promoting crop diversification, and maintaining a semi-permanent to permanent soil cover within the cropping system (TerAvest *et al.*, 2015; Steward *et al.*, 2018; Mupangwa *et al.*, 2021). It has been promoted as a land use management practice, climate risk reducing option, and potential avenue to increase sustainable crop production (Franke *et al.*, 2018; Leonardo *et al.*, 2018; Mupangwa *et al.*, 2021). Some of the adopted CA practices by smallholder farmers include crop establishment technologies such as manually prepared planting basins, jab planter, and dibble sticks (Ngoma *et al.*, 2015; Kidane *et al.*, 2019).

As CA evolves in Southern Africa, considerable debate has emerged about the ideal crop establishment techniques for optimal results. Larger basins (15 × 15 cm, wide × deep) require more labour but are more effective for water harvesting, while smaller basins (15 × 5 cm) are less labour-intensive and help prevent crop drowning and waterlogging during heavy rainfall (Nyagumbo *et al.*, 2016). CA planting basins have also been found to increase crop yield, improve soil quality, and improve input use efficiency (Fonteyne *et al.*, 2021; Mupangwa *et al.*, 2021).The basins can be useful in coping with rainfall variability and moisture deficits (Cooper *et al.*, 2008; Ngwira *et al.*, 2014) as they increase the capture of run-off water, enhance infiltration, and improve conservation of soil moisture in the root zone, thereby potentially mitigating in-season dry spells (Ngwira *et al.*, 2014; Thierfelder *et al.*, 2016). As other CA techniques, direct seeding using dibble stick or jab planter has also proved to be more profitable and less risky and also deliver labour reductions ranging between 45 and 55% relative to the conventional and traditional farmer practice (Mupangwa *et al.*, 2019).

Crop diversification through legume inclusion into cereal-based cropping systems has also been promoted as a solution to reduce yield losses, enhance stability, and ensure nutritional security in a sustainable manner (Mugiyo *et al.*, 2018; Nyamayevu *et al.*, 2024). SSA farming systems are predominantly based on imbalanced diets mainly from cereal mono-cropping systems with limited crop diversification (Akombi *et al.*, 2017; Mhlanga *et al.*, 2021). Dependence on staple cereals such as maize has led to nutritional deficiencies, leading to stunting, underweight, and wasting particularly in children (Wheeler and Von Braun, 2013; Mhlanga *et al.*,2021). Cereal grains such as maize are valuable for their substantial energy and modest protein levels, while legumes typically yield much less than maize but contain more than twice the protein content (Pleasant 2016; Temba *et al.*, 2016). Therefore, integration of legumes into maize-based cropping systems can potentially increase protein accessibility, enhance dietary diversity, and improve the nutrition balance particularly to resource poor farmers (Mhlanga *et al.*, 2021; Temba *et al.*, 2016).

Overall, this study was carried out (1) to compare the performance of maize cultivated as sole crop or mixed with grain legumes either as intercropping or rotation, in terms of maize grain yield and total systems' nutritional (protein and energy) productivity and (2) to evaluate maize grain yield under minimum tillage crop establishment techniques. We hypothesised that (i) legume integration into maize-based cropping systems increases maize grain and nutritional yield per unit of land and (ii) CA basins increase maize yield as compared to jab planter and dibble stick during low rainfall seasons but leads to yield reductions under high rainfall conditions.

Material and methods

Site description

The rain-fed study was conducted in Malawi, at Chitala Research Station (−13.683 latitude, 34.267 longitude). The research station is located in the semi-arid region of Malawi's lowland ecological region at an altitude of 615 m above sea level (m a.s.l) and experiences high rainfall variability as well as high temperatures (Nyagumbo *et al.,* 2017). Rainfall seasons have a unimodal pattern, and they range between 550 and 900 mm per year (Nyagumbo *et al.,* 2017). The crop growing season spans between November and April and is characterised by in-season dry spells that are more frequent in January and February. The trial was established by the project Sustainable Intensification of Maize-Legume Systems in Eastern and Southern Africa (SIMLESA, https://simlesa.cimmyt.org/) with the objective of developing sustainable and resilient CA-based cropping systems for southern Africa.

Experimental design

The trial was initiated in the 2010/11 crop season and was laid out in a Randomized Complete Block Design (RCBD) with cropping systems as the main treatments. In the 2014/15 season, the trial was modified by introducing different basin sizes in the CA basin maize sole system. This system was divided into small basins and big basins for crop establishment, allowing us to assess the impact of basin size while maintaining consistent plot dimensions throughout the experiment. The trial had three replications for each cropping system, as shown in Table 1, resulting in 36 plots (20 × 15 m). Herein, we present data from four cropping seasons, from 2014/15 to 2017/18, covering the period following the introduction of small and big basins as crop establishment techniques.

Cropping systems tested included conventional maize sole, conventional maize-legume intercrop, CA maize sole, CA maize-legume intercrops, and CA maize-legume rotations (Table 1). Crop establishment techniques involved (1) conventional ridge and furrow system, (2) CA jab planter, (3) CA tapered wooden dibble sticks, and (4) CA planting basins (small and big basins) (Tables 1 and 2). In recognition of the most widely cultivated legumes, local dietary and market preferences, some legumes were designated and implemented in CA cropping systems (Mupangwa *et al.,* 2021): cowpea (*Vigna unguiculata*.L), groundnut (*Arachis hypogaea*.L), and short-season and long-season pigeon pea (*Cajanus cajan*.L) in rotation and intercrop systems with maize (*Zea mays*.L), the staple and primary test crop (Table 1). These legume crops can significantly enhance household nutritional status by improving both human (protein) and soil (nitrogen) nutrition (Hussain *et al.,* 2022; Saxena *et al.,* 2016). For this analysis, we used data from 10 treatments, excluding treatments involving long-season pigeon pea (rotation and intercrop systems) due to insufficient grain yield data.

Crop management

Local agronomic recommendations were implemented including the use of basal fertilisers 23:21:0 + 4S (N:P:K) at 100 kg ha^{-1} at seeding. Uniform top dressing urea (46% N) was applied to maize at 150 kg ha^{-1} four to seven weeks after planting. A pre-emergence herbicide glyphosate [*N*-(phosphonomethyl) glycine, 41% active ingredient] was applied immediately after seeding or two to three days after seeding. After maize emergence, hand weeding was carried out when necessary and whenever weeds reached 10 cm height and radius for stoloniferous weeds. Weeds remaining near or after harvest were manually removed to prevent weed seed production.

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Table 1. Description of the cropping systems tested at Chitala Research Station, over four consecutive cropping seasons

Treatment name	Cropping system	Treatment description
Conventional farmer ridges maize sole	Conventional sole	Maize grown in conventional ridge and furrow system, without residue.
Jembe hole (CA basin) maize sole	CA sole	Sole maize planted in small or big basin, with residue cover applied at 2.5–3 t ha^{-1}.
Dibble stick maize sole	CA sole	Sole maize planted using a dibble stick, with residue cover applied at a rate of 2.5–3 t ha^{-1}.
Jab planter maize sole	CA sole	Sole maize planted using a jab planter, with residue cover applied at 2.5–3 t ha^{-1}.
Jembe hole maize-short pigeon pea intercrop	CA intercropping	Maize grown simultaneously with short-season pigeon pea, in big basins, and residue cover applied at 2.5–3 t ha^{-1}.
Jembe hole maize-long pigeon pea intercrop	CA intercropping	Maize grown simultaneously with long-season pigeon pea, in big basins, and residue cover applied at 2.5–3 t ha^{-1}.
Jembe hole maize-cowpea intercrop	CA intercropping	Maize grown simultaneously with cowpea, in big basins and residue cover applied at 2.5–3 t ha^{-1}.
Jembe hole maize-cowpea rotation	CA rotation	Maize grown in rotation with cowpea annually, in big basins and residue cover applied at 2.5–3 t ha^{-1}.
Jembe hole cowpea-maize rotation	CA rotation	Cowpea grown in rotation with maize annually, in big basins and residue cover applied at t ha^{-1}.
Jembe hole groundnut-maize rotation	CA rotation	Groundnuts grown in rotation with maize annually, in big basins and residue cover applied at 2.5–3 t ha^{-1}.
Jembe hole maize-groundnuts rotation	CA rotation	Maize grown in rotation with groundnuts annually, in big basins and residue cover applied at 2.5–3 t ha^{-1}.
Conventional farmer ridge maize-long-season pigeon pea intercrop	Conventional intercropping	Maize grown simultaneously with long-season pigeon pea in the conventional ridge and furrow system, with no application of crop residue.

All the CA cropping systems reported here incorporated at least two of the three CA principles involving minimum tillage with CA planting basins (15 × 15 cm), maize-legume crop diversification systems, and soil cover through crop residues and were tested relative to the maize sole in traditional ridge and furrow system. For this analysis, data from 10 treatments were used, excluding those involving long pigeon pea due to insufficient grain yield data.

Planting was carried out on the same plots every season under rain-fed and minimum tillage conditions. CA basins were prepared before seeding and basal fertiliser incorporated in them; the same permanent planting stations were maintained and used repeatedly in each season. In CA treatments, residue management involved the application of at least 2.5–3 Mg ha^{-1} of residues from the previous maize crop. If surface residues have been grazed or removed, same quantity of residues (preferably maize) was uniformly distributed across all plots. A target maize plant population of 53 000 plants ha^{-1} was established across all plots.

Maize and legume yields

Grain and biomass yields, as well as plant populations, were measured annually at harvest from each plot over seven consecutive cropping seasons. Cereal and legume grain yields were determined from a sub-plot of 5 m × 2 rows in each cropping system at the end of each cropping cycle. The distance between rows on each check plot was measured to ensure accurate row spacing. For cereals, the number of cobs per sample was counted and weighed using a hanging digital scale. A random sample of eight (8) cobs was then weighed, air-dried, re-weighed, shelled, and the grain finally weighed. For legumes, the number of plants in the net plot was counted, and all plants, including the pods, were weighed using a hanging digital scale. Pods were separated from the other aboveground biomass, weighed, and a subsample of between 500 g and 1000 g was air-dried, re-weighed, threshed, and the grain weighed to the nearest 0.1 g. The air-dried grain weight from each plot was corrected to 12.5% moisture content after determining its moisture with a grain moisture metre and then standardised to a hectare basis. Aboveground biomass was measured by weighing the stalks and leaves after removing the cobs/pods. A subsample of stalks was then taken, weighed, air-dried, and reweighed after 2–3 weeks. The original fresh biomass was

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Table 2. Description of the crop establishment techniques tested at Chitala Research Station, over four consecutive cropping seasons

Establishment technique	Description
CA + Big basin	Prepared by a hand hoe locally known as *jembe* hoe. Basins measured 15 cm long, 15 cm wide, and 15 cm deep, Placed at 75 cm between rows, 75 cm between basins in the row. Four maize plants per station thinned to 3 after germination.
CA + Small basin	Prepared by a *jembe* or hand hoe. Basins measured 10 cm long, 10 cm wide, and 5 cm deep. Placed at 75 cm between rows, 75 cm between basins in the row. Four maize plants per station thinned to 3 after germination.
CA + Dibble stick	Planting stations were prepared by a pointed stick. Holes for seed and basal fertiliser placement were opened at 5cm depth. Maize planting stations were placed 25 cm in-row and 75 cm. Two seeds per station thinned to one plant per station after emergence.
CA + Jab planter	Planting stations were prepared by a handheld jab planter. Adjacent holes for seed and basal fertiliser placement were opened after receiving effective planting rains. Calibrated before seeding aiming seed rate of about 53 333 plant/ha at 75 cm spacing. Two seeds per station thinned to one plant per station after emergence.
Conventional ridge and furrow	Ridges are raised beds of soil and furrows are the depressions or troughs between them. Ridges spaced to conform to local recommendations of 75 cm between rows and 25 cm between plants. Two seeds per station thinned to one plant per station after emergence

Crop establishment techniques reported in this study were exclusively applied in maize sole cropping systems. Ridge and furrow is a traditional and widely used crop establishment technique in Malawi. CA + crop establishment techniques aimed at minimum tillage while retaining crop residues.

corrected for moisture loss using the ratio obtained from the air-dried subsamples and then added to the grain weights to determine the total aboveground biomass expressed on a hectare basis. Annual datasets drawn from the experiment were progressively assembled into one common MS-Excel spreadsheet, and key variables were captured.

For nutritional yield assessment, the research focused on caloric energy and protein contribution of each cropping system (this accounted for sum of all component crops' protein and energy yields for a cropping system), as food must supply adequate energy for daily activities while protein is used to provide amino acids, which are essential for cell and organ functions (Pleasant, 2016). For total cropping system nutritional productivity, the sum of all component crops' protein and energy yields, grain protein, and energy equivalent yields were calculated using the grain protein and calorie conversion factors obtained from USDA Food Data Central (USDA, 2021). On energy, maize, cowpea, groundnuts, and pigeon pea seeds were reported to contain approximately 365, 343, 567, and 446 kcal per 100 g, respectively. In terms of protein content, maize, cowpea, groundnuts, and pigeon pea seeds were assumed to contain 9.42%, 23.8%, 25.8%, and 36.5% protein in their unprocessed form. Therefore, both maize and the legume (ground nut, cowpea, and pigeon pea) grain yield was converted into protein and energy yield. Protein yield was reported in kg ha^{-1} and energy as GJ ha^{-1}. While protein and caloric values may vary after grain processing and cooking, we present them as an indicator of potential protein and energy availability from each treatment. The equations used for calculating energy and protein yields varied across cropping systems (Supplementary Material: Sup Table 1).

Statistical analysis

Using R (version 4.3.1), linear mixed models were fitted to test for significant differences in maize grain, energy and protein yield across treatments, seasons, and cropping systems and to quantify

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the sources of residual variance in the data. The tested cropping systems, crop establishment techniques, and cropping seasons were treated as fixed factors, while the replicate blocks were treated as random factors. Linear mixed models were fitted using the *lmer()* function of the lmerTest R package (Kuznetsova *et al.*, 2017). Analysis of variance was conducted to test the significance of the fixed effects at 5% significance level using the *anova()* function in R. Finally, means and standard errors of the mean were predicted for each cropping system using the *emmeans()* function of the emmeans R packages (Searle *et al.*,1980). Using the r-part package in R, Classification and Regression tree (CART) analysis (Breiman *et al.*, 2017) was done as an exploration model to supplement the ANOVA with the amount of variation in maize yield accounted for input factors. Maize grain yield was then partitioned as influenced by input factors (seasons, crop establishment techniques, and cropping systems). The tree was built by partitioning the maize grain yield variations into different nodes; each node of a tree was associated with a particular set of independent variables that were split by a specific test on a feature. Starting from the root node (first parent), each node was then split into left and right child nodes using the mean square error (MSE) statistical splitting criteria. The nodes were then divided in a hierarchical design, and they became parent nodes to their subsequent children nodes. The CART procedure estimates and calculates the yield variability accounted for by each factor and generates variable importance scores. In other words, this analysis facilitated selection of the most important variables and measures their relative importance.

Results

Seasonal rainfall

Total monthly rainfall and cumulative annual rainfall provide insights into the beginning, mid- to late-season water availability for each cropping year from 2014/15 through 2017/18 (Figure 1a and b). In 2014/15 season, rainfall peaked in January at 260 mm, totaling 751 mm along the season. In 2015/16 season, the rainfall peak (284 mm) was in March, while the total rainfall for the season was 562 mm. During the 2016/17 season, the wettest month was January (323 mm), contributing to a seasonal total of 844 mm. Lastly, rainfall peaked at 299 mm in February and the 2017/18 season reached a total of 890 mm (Figure 1a and b). Annual rainfall was then categorised as follows: less than 600 mm was classified as a 'low' rainfall season, between 600 and 700 mm as 'medium,' and above 800 mm as 'wet'. These classifications denote different levels of rainfall intensity for the purpose of discussion in this study.

Regression trees

The regression tree results present the contribution of each key independent factor variables to the maize grain yield (Figure 2). After yield partitioning, maize grain yield variation was accounted for by season (60%), cropping systems (29%), and crop establishment techniques (12%). The first parent (top) node had an overall mean maize yield of 3879 kg ha^{-1}. This was followed by two child nodes separating seasons into two groups with 2016/17 cropping season yielding significantly higher than the other three cropping seasons (2014/15, 2015/16, and 2017/18). Subsequently, maize grain yield was separated by cropping systems, with rotation systems (maize-cowpea rotation and maize-groundnut rotation), conventional and CA maize sole system performing better than the intercropping systems (maize-cowpea intercrop and maize-pigeon pea intercrop). Further down the tree, yield was separated by crop establishment techniques, with the jab planter performing better in the 2016/17 cropping season, while the big basin system outperformed in 2015/16. This analysis suggests that season is the most influential factor, accounting for most of the variation in maize grain yield, with highest maize yield being observed in 2016/17 cropping season under jab planter CA sole system (Figure 2).

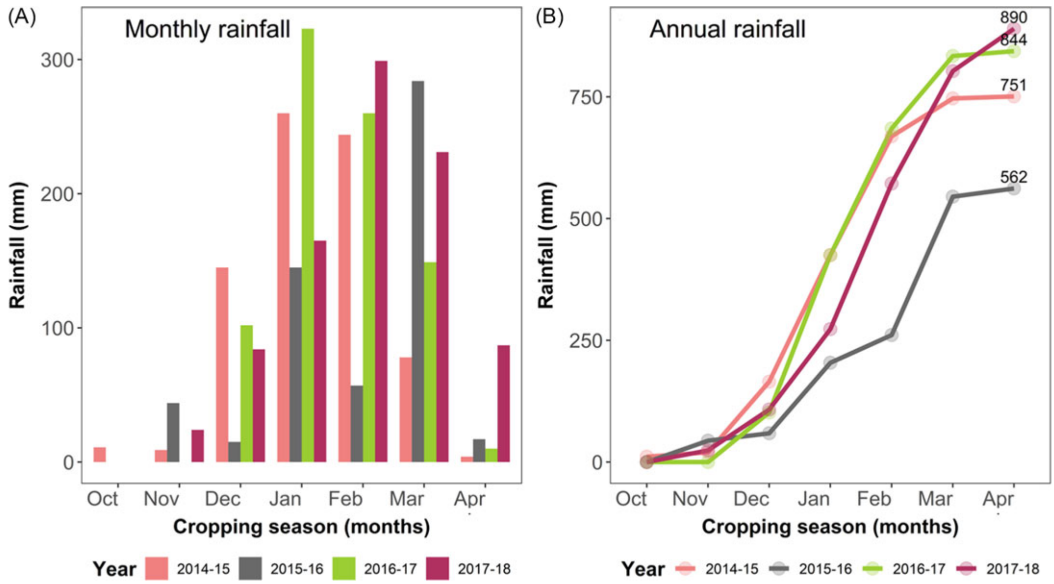

Figure 1. Seasonal rainfall received during experimentation period in Malawi Chitala (2014–2018).

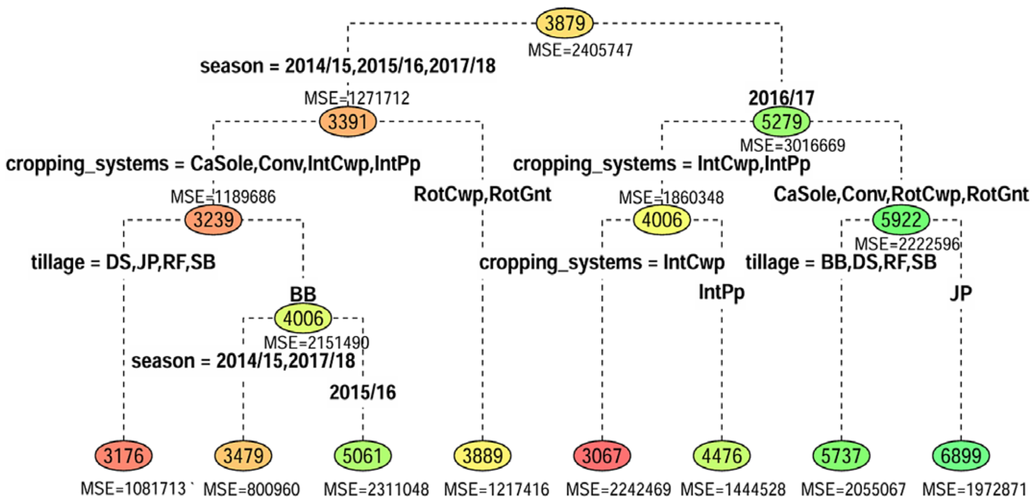

Figure 2. Summarised Classification Regression Tree showing partitioned contributions of different factors in maize grain yields (kg ha^{-1}). Mean square error (MSE) based on maize yield (kg ha^{-1}) and used by CART for splitting factor levels. Cropping systems: RotCwp = maize-cowpea rotation, IntCwp = maize-cowpea intercrop, RotGnt = maize-groundnut rotation, IntPp = maize-pigeon pea intercrop, MzSole = maize sole, and Conv = conventional sole. Crop establishment techniques: BB = big basin, SB = small basin, DS = dibble stick, JP = jab planter, and RF = ridge and furrow.

Maize grain yield and total biomass as affected by crop establishment techniques and seasons

Crop establishment techniques and seasonal variations significantly affected maize grain and biomass yields. To understand this, data were plotted for each season separately (Figure 3). During the 2014/15 (medium rainfall) and 2015/16 (low rainfall) seasons, planting basins (big and small basins) and ridge-furrow systems tended to increase yields compared to jab planter and dibble stick systems (Figure 3a–d). However, the same systems (planting basins and ridge-furrow) tended

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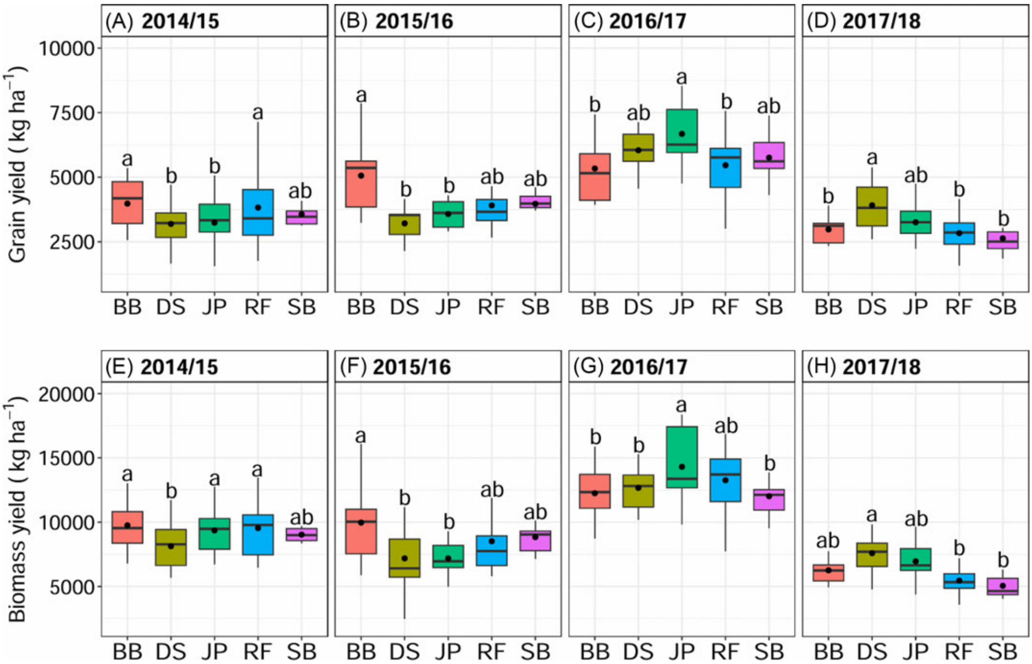

Figure 3. Interaction effects of season and crop establishment techniques on maize grain yield and total biomass during experimentation in Malawi Chitala (2014–2018). Circles inside boxes represent means, horizontal bar in the middle of each box represents the median, while lower and upper box plot boundaries represent the 25th and 75th percentiles, respectively. Lower and upper whiskers represent the minimum and maximum values, respectively. For each cropping season letters, above boxes indicate significant differences between respective crop establishment techniques at 5% significance level. Crop establishment techniques: BB = big basin, SB= small basin, DS= dibble stick, JP= jab planter, and RF = ridge-furrow.

to reduce yields in the 2016/17 and 2017/18 seasons. In the 2015/16 season, the big basin and small basin systems produced maize grain yields of 5061 and 3969 kg ha^{-1}, respectively. These yields surpassed those from the jab planter and dibble stick, which yielded 3476 and 3213 kg ha^{-1}, respectively. Conversely, the yields from the basin and ridge-furrow systems declined compared to those of direct seeding with dibble stick and jab planter during the wet seasons (2016/17 and 2017/18). In the 2017/18 season, the big basin, ridge-furrow system, and small basins produced 2980, 2836, and 2634 kg ha^{-1}, respectively. In contrast, the dibble stick and jab planter systems yielded better, producing 3915 and 3256 kg ha^{-1}, respectively. The same trend was observed in biomass production (Figure 3e–h), where the basin system produced more in 2014/15 and 2015/16 cropping seasons, but less in 2016/17 and 2017/18.

On basin sizes, larger basins caused higher maize grain yield during the medium and low rainfall seasons of 2014/15 and 2015/16. However, during seasons with persistent and significant monthly rainfall, particularly when total annual rainfall exceeded 800 mm in 2016/17 and 2017/18, the yield differences between basin sizes became statistically insignificant.

Maize grain yield under varying cropping systems

Similar to the crop establishment techniques, significant differences in maize grain yield among cropping systems were observed across four consecutive seasons (Figure 4). There was some variation among seasons, but maize-legume rotation systems consistently yielded among the highest, while maize-legume intercropping systems had the lowest yields among all systems

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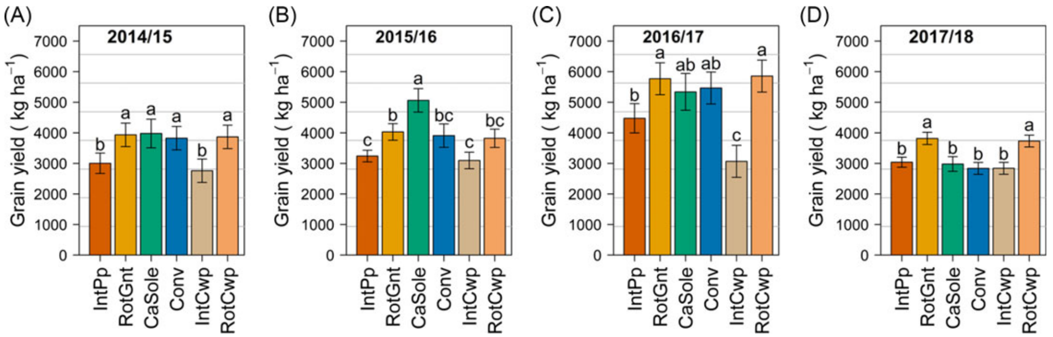

Figure 4. Mean maize grain yield of the tested cropping systems over four consecutive growing seasons (2014/15–2017/18) in Chitala, Malawi. For each season, different letters above bars indicate significant differences between respective cropping systems at 5% significance level. Cropping systems RotCwp = maize-cowpea rotation, IntCwp = maize-cowpea intercrop, RotGnt = maize-groundnut rotation, IntPp = maize-pigeon pea intercrop, MzSole = maize sole, and Conv = conventional sole.

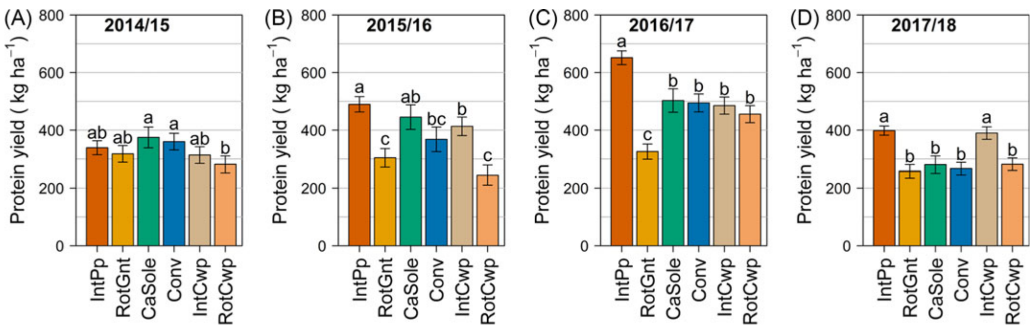

Figure 5. Total system protein yield of the tested CA cropping systems over four consecutive growing seasons at Chitala Research Station in Malawi. For each season, different letters above bars indicate significant differences between respective cropping systems at 5% significance level. Cropping systems: RotCwp = maize-cowpea rotation, IntCwp = maize-cowpea intercrop, RotGnt = maize-groundnut rotation, IntPp = maize-pigeon pea intercrop, MzSole = maize sole and Conv = conventional sole.

between 2014 and 2017. The yield advantage of maize-groundnut rotation resulted in increases of 1173, 878, 2700, and 987 kg ha^{-1} above the maize-cowpea intercrop over the four consecutive seasons. In the intercropping systems, maize-pigeon pea consistently outperformed maize-cowpea, yielding 9%, 4%, 45%, and 7% more than maize-cowpea intercrop along the four seasons. Additionally, the maize-cowpea rotation consistently outperformed the maize-cowpea intercropping system, with yield increases ranging from 725 to 2700 kg ha^{-1} across seasons.

Protein and energy yields

Protein yield varied significantly across seasons and among cropping systems (Figure 5). Despite the compromised maize grain yields, maize-legume intercropping systems often yielded more protein compared to other systems. Crop rotation systems consistently generated the lowest protein output among all systems. In 2014/15, there were no significant differences in protein yield among cropping systems except for maize-cowpea rotation, which had the lowest protein yield at 281 kg ha^{-1} (Figure 5a). Along three seasons, maize-pigeon pea intercropping consistently had higher protein yield compared to all other cropping systems, that is, +9.5% in 2015/2016, +29.1% in 2016/2017 compared to CA sole, and +2.2% in 2017/2018 relative to cowpea intercropping.

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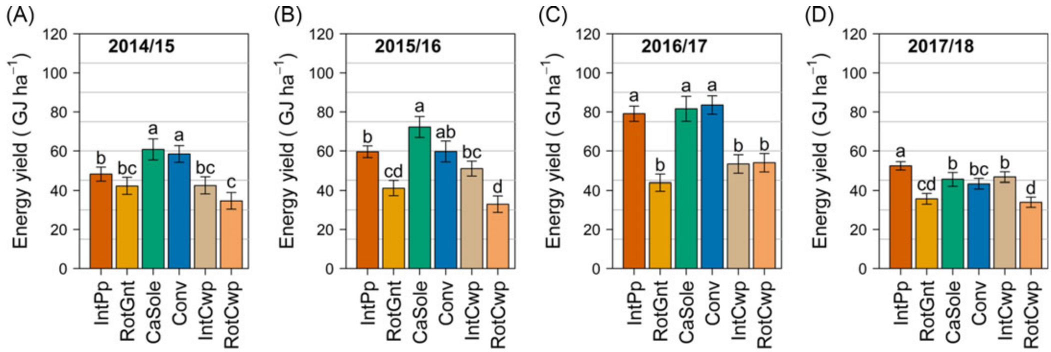

Figure 6. Total system energy yield of the tested CA cropping systems over four consecutive growing seasons at Chitala Research Station in Malawi. For each season, different letters above bars indicate significant differences between respective cropping systems at 5% significance level. Cropping systems: RotCwp = maize-cowpea rotation, IntCwp = maize-cowpea intercrop, RotGnt = maize-groundnut rotation, IntPp = maize-pigeon pea intercrop, MzSole = maize sole, and Conv = conventional sole.

As found for protein yield, energy yield also varied across seasons and cropping systems (Figure 6). Sole systems (CA sole and conventional) consistently ranked among the best systems in terms of energy yield, closely followed by maize-pigeon pea intercrop, which surpassed all other systems and yielded 52 GJ ha^{-1} in 2017/18 (Figure 6d). Conversely, maize-cowpea rotation consistently had low energy yield.

Discussion

Crop establishment as affected by rainfall

The significant interaction between crop establishment techniques and cropping seasons (Figure 3) highlights the substantial impact of season characteristics on the effectiveness of crop establishment techniques. The basin and ridge-furrow systems excelled in seasons with low (562 mm) and medium (739 mm) rainfall, particularly in 2014–15 and 2015–16. However, they were outperformed by the jab planter and dibble stick when wet conditions prevailed. Simply put, CA basins efficiently capture rainfall, ensuring moisture availability during dry periods but can lead to waterlogging in years with excessive rainfall due to saturated soils. These results support the notion that CA basin systems can be an alternative and most preferred to drought-prone regions of Southern Africa (Mupangwa *et al.*, 2017). It also demonstrated that basin systems can be advantageous in mitigating the negative impacts of deviations in rainfall, especially when it is below average in dry environments (Nyagumbo *et al.*, 2016). This confirms the idea that CA technologies can help rain-fed systems adapt to erratic rainfalls, drought, and heat stress (Steward *et al.*, 2018) as it reduces and buffers farmers from the negative impact of rainfall variability (Mupangwa *et al.*, 2019). This study acknowledges that seasonal variations in daily rainfall and temperature impact crop establishment techniques performance, emphasising the need for detailed climatic assessments in future studies to enhance crop establishment evaluations.

The CA basin system performance could potentially be attributed to its higher water harvesting capacity that promotes deeper water infiltration, better soil profile recharge, and enhanced water retention capacity compared to dibble stick and jab planter (Nyagumbo *et al.*, 2016). Results obtained with respect to the size of basins also suggest that relatively large basins (15 × 15 cm) could be the preferred option for low rainfall seasons, while the small basins could be ideal for relatively wetter seasons. Our results endorse conclusions by various CA and crop production studies from SSA regions where CA planting basins were found to have a better water retention capacity and have potential to increase yields by 15–75% in semi-arid areas (Dube *et al.*, 2014). In

Zambia, CA planting basins doubled the maize yield under traditional tillage systems (Bwalya *et al.*, 2011), but they reduced yield on sites prone to waterlogging (Gatere *et al.*, 2013). This suggest that benefits of CA are more apparent under rain-fed agriculture systems where it has potential to enhance smallholder farmers resilience against seasonal dry spells (Fonteyne *et al.*, 2021; Pittelkow *et al.*, 2015).

During the 2016–17 and 2017–18 cropping seasons, two wet seasons with total rainfall exceeding 800 mm, basin systems reduced yields in contrast to direct seeding technologies. Dibble stick and jab planter turned out to be viable alternatives in situations where CA basins fail due to excessive rainfall. Thus, crop establishment techniques performance was rainfall-dependent with no benefits from basin systems on high rainfall conditions where soil moisture conservation was less critical for the crop and direct-seeded dibble techniques provided a better crop establishment option (Nyagumbo *et al.*, 2016). Based on this, it is reasonable to assert with confidence that CA basins when implemented in waterlogging soils and high rainfall environments result in depressed yield compared to the direct seeding systems. This is attributed to excessive water harvested by the basins (Gatere *et al.*, 2013) and accelerated nutrient leaching (Geerts & Raes, 2009). These results agree well with regional findings in on-farm studies from southern Africa that put forward that CA basins can have negative impact on yields whenever incessant rainfall events lead to waterlogging (Mupangwa *et al.*, 2012; Nyagumbo *et al.*, 2020). These findings also align with results from the ESA region, showing that CA investments can boost maize yields by up to 95% under rainfall below 700 mm but may reduce yields when rainfall exceeds 1300 mm (Nyagumbo et al., 2020). Finally, our results substantiate the promotion of CA planting basins as a potential seeding technology that offers a chance for better crop yields in rain-fed cropping systems where moisture conservation during critical crop phases may increase crop yields or at least reduce the risk of complete crop failure.

Maize grain yield across cropping systems

Rotation systems consistently outperformed sole and intercropping systems in terms of maize grain yield (Figure 4). While intercropping has its merits, it tends to be less effective in maximising maize grain yield compared to rotation systems. Across the study period, the CA sole system performed rather moderately in terms of maize yield, despite the setbacks of mono-cropping in it. The CA sole system as implemented here still embraced two of the three CA principles (Kassam *et al.*, 2009): (1) reduced soil disturbance and (2) provision of surface cover. Application of these two CA principles possibly contributed to enhanced soil structure, moisture retention, and nutrient cycling. The improvements in soil pH (Banda *et al.*, 2018; Zerihun *et al.*, 2014) and increased soil biological activity (Micheni *et al.*, 2016) could also trigger the availability of other nutrients besides soil N, increasing maize yield even in CA systems without legume incorporation (Mupangwa *et al.*, 2021).

Increases in maize grain yield under rotation system can also be explained by the high legume density (i.e., the legume phase of the rotation), which may result in enhanced biological nitrogen fixation and then supplement the applied mineral nitrogen (Mutsamba *et al.*, 2020; Mupangwa *et al.*, 2021). On the other hand, high plant density in intercropping systems combining maize and the associated legumes is usually 1.5–2 times the density of plants in sole crops, thus resulting in inter- and intraspecific competition for essential resources such as nutrients, water, and light between maize and the companion legume (Madembo *et al.*, 2020; Njira *et al.*, 2021). Managing an intercrop can also demand higher labour input, which may impact the timing of operations and pose significant challenges to successful intercropping in Southern Africa (Nyagumbo et al., 2020). Conversely, rotation systems, with less crop competition, maximise the efficient use of space and natural resources (Mupangwa *et al.*, 2021) and has demonstrated significant maize grain yield boost with remarkable yield increase of over 40% (Nyagumbo *et al.*, 2016, 2024).

https://doi.org/10.1017/S0014479724000267 Published online by Cambridge University Press

In intercropping systems, maize-pigeon pea significantly outperformed maize-cowpea. Pigeon pea develops much slower initially, and its highest demand for water and nutrients occurs after maize has been harvested and as such, there will be little competition with the primary maize crop (Kimaro *et al.*, 2009; Madembo *et al.*, 2020). With SSA soils widely degraded and infertile with N as a major limiting factor to productivity, and farmers having limited access to amendments such as inorganic fertilisers and manure, rotation systems therefore stand as an imperative potential solution to these challenges (Okalebo *et al.*, 2006; Mhango *et al.*, 2013), particularly where land area is not limiting.

Protein and energy: cropping systems nutritional yield

The likelihood of protein nutritional security was reliably high in intercropping systems with maize-pigeon pea out yielding other systems in most seasons, while conventional and CA sole systems exhibited energy yield advantage (Figures 5 and 6). Intercropping systems also outperformed rotation systems in terms of both energy and protein yield, largely because intercropping effectively consolidates the combined energy and protein yields of both cereal and legume crops on the same plot each year, whereas in rotational systems each crop's contribution must be halved to accommodate both crops as explained on nutritional yield calculation equations (Supplementary Material: Sup Table 1). Overall, results imply that intercropping systems surpass rotation systems in achieving nutritional security.

High energy yield on sole system may be attributed to the inherent high energy density of maize cereal (Nuss and Tanumihardjo, 2010; Ranum *et al.*, 2014). Maize grain contains starch (72% to 73% of total kernel weight), which is a complex carbohydrate and source of energy (FAO 1992; Sandhu and Singh, 2007). In contrast, legumes naturally yield much less energy than maize but are a good source of protein and contain more than twice the protein of cereals (Pleasant, 2016; Saxena *et al.*, 2016; Temba *et al.*, 2016). These results illustrate that consumption of staple cereals such as maize may boost energy availability but does not improve nutritional outcomes (Rajendran *et al.*, 2017); hence, diets based on cereals alone are not capable of ensuring nutritional security (Rajendran *et al.*, 2017; Mhlanga *et al.*, 2021). Dominance of sole maize systems can have negative effects on household nutrition as maize mostly contributes calories without providing diverse range of essential nutrients (Thierfelder *et al.*, 2024). Therefore, integrating nutrient-rich legumes into maize-based cropping systems may be a practical and sustainable way to enhance protein access and boost dietary diversity for SSA's resource-poor smallholder farmers since animal protein is beyond reach of many (Mkwambisi *et al.,* 2023; Nyamayevu *et al.*, 2024; Temba *et al.,* 2016). SSA nutritional policies must therefore prioritise diversification of cereal-based diets by introducing legumes for higher protein content in daily food.

Conclusion

Maize grain productivity varied with crop establishment technique and cropping systems. Planting basins along with ridge and furrow systems showed better performance compared to other systems in seasons with low to moderate rainfall. On the other hand, establishment techniques involving much less soil surface disruptions such as the dibble stick and jab planter performed better when rainfall was relatively consistent and high. Our findings also indicate that larger planting basins (15 × 15 cm) improve maize grain yield during seasons of low and scant rainfall but result in reduced yields under high and persistent rainfall. Therefore, the choice of planting basin sizes and whether or not to use dibble stick and jab planter needs to be guided by location or site-specific seasonal rainfall forecasts for best results. This study also confirms that maize-legume rotations significantly improve maize grain yield, while maize-legume intercropping systems may lead to its reduction. Maize-legume intercrops, however, were found to be advantageous in increasing nutritional yields compared to rotation systems, and thus intercrops

https://doi.org/10.1017/S0014479724000267 Published online by Cambridge University Press

can be important diversification options for nutrition security particulary for resource-poor smallholder farmers where animal protein is often out of reach. Integrated maize-legume rotation/intercropping systems under CA practices can play a role in increasing maize grain yield or improving nutritional security status in semi-arid environments of SSA.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479724000267

Acknowledgements. The authors of this paper greatly acknowledge the Australian Center for International Agricultural Research (ACIAR) for their generous long-term financial support under Grant No. CSE/2009/024 that enabled this study to be conducted under the project Sustainable Intensification of Maize-Legume Systems in Eastern and Southern Africa (SIMLESA). We are also grateful to Mr. Donald Siyeni of the Department of Agricultural Research Services, Malawi, for his efforts in supervising the field research activities that enabled the data used in this study to be generated.

Competing interests. None.

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