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ORIGINAL PAPER

Management of maize-legume conservation agriculture systems rather than varietal choice fosters human nutrition in Malawi

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Abstract

Malawi smallholder farmers are facing climate-induced challenges that have increased food and nutrition insecurity in the country, thus sustainable intensification practices has been widely recommended. The objective of this study was to assess the effects of cropping systems with improved varieties on total system productivity and nutrition under different environments. The study involved on-farm experiments in ten communities in Central and Southern Malawi, incrementally established from 2005/2006 to 2018/2019 cropping seasons. Each community had six demonstration plots with three main treatments: conventional ploughing (CP): sole maize grown on seasonally constructed ridges and furrows; no-tillage (NT): sole maize grown on retained ridges with minimum soil disturbance and residue retained; and Conservation agriculture (CA): maize intercropped either cowpea, pigeon pea or groundnut on retained ridges as in NT. Our results show that total system nutrition was higher in CA treatments than NT and CP. The yields of maize were at least 800 kg ha^{-1} higher in CA and NT than CP despite the variety that was grown. Legume yields were also higher under CA and NT than CP. High protein yield was observed in CA systems (at least 100 kg ha^{-1} higher than CP) where maize and legume intercrops were rotated with grain legumes. Our results show nutrients and energy gains in CA and NT systems that can be invested in practices that increases the resilience of smallholder farmers to climate change. Conservation agriculture and NT systems have more influence on productivity of smallholder farms, despite the genotypes used (hybrids or OPVs).

Keywords Intercropping · Maize varieties · No-tillage · Nutrition · Rotation

1 Introduction

Food and nutrition insecurity in Southern Africa continues to worsen due to climate, social and economic conditions prevalent in the region. Erratic rainfall patterns, heat and drought stress and shortening of the growing season accompanied by declining soil fertility reduces the crop yields. Furthermore, the difficult economic conditions in the region results in farmers' having limited access to agricultural inputs such as fertilizer and certified seeds which further worsens food and nutrition insecurity. This is further exacerbated by the poor markets, which makes it difficult for farmers to adopt certain technologies despite their importance to smallholder households (Bjornlund et al., 2020). Approximately 25% of Southern Africa's population is undernourished (FAO & ECA, 2018), which compromises the regions' capability to meet the Sustainable Development Goal 2 target, "End hunger, achieve food security and improved nutrition and promote sustainable agriculture". Approximately 80% of food required to feed a growing population in Southern Africa is produced by smallholder farmers. However, most rural farmers have small landholding sizes (on average 2 ha per household, Lowder et al., (2016), FAOSTATS, 2023) and limited access to inputs to intensify their farming systems adequate to reach the household living income (Marinus et al., 2022). To overcome this challenge, farmers could intensify their cropping systems making use of improved management practices, however this requires significant investment from farmers and often new knowledge (Marinus et al., 2022).

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Farming systems in Malawi are dominated by maize (*Zea mays* L.) as the staple crop, frequently cultivated in intercrops with less focus on soil fertility improvement. Malawi smallholder farmers have access to subsidized inputs from the government, which gives them an advantage over some other farmers in Southern Africa. However, due to several factors including inadequate weeding, late application of fertilizers, low soil organic matter and poor soil quality including high soil acidity and low phosphorus their maize yields are still low (Snapp et al., 2014). The average maize yield in smallholder farms ranges between 2–3 tons ha^{-1} depending on the quality of the cropping season. Nevertheless, despite an average family size of 6 people per household, each requiring around 1500 kg of maize per year, farmers are left with a limited surplus for sale to meet their annual household needs (FAOSTATS, 2023; Stevens & Madani, 2016). The over-reliance of farmers on maize for food security results in imbalanced diets that worsen the malnutrition status of households in Malawi (Mazunda & Droppelmann, 2012). Other crops such as grain legumes (e.g., groundnut (*Arachis hypogea* L), cowpea (*Vigna unguiculata* Walp), and pigeon pea (*Cajanus cajan* Millsp)) are also grown, but they occupy less than 30% of the arable land area. Grain legumes are crucial in smallholder farmers' diets because they are a rich source of dietary protein, fiber, minerals (iron and zinc), phytochemicals and vitamins (including vitamin B) (Polak et al., 2015). Most of the crops are grown on annual ridges (constructed every year) of 75 cm to 90 cm row spacing and 20–50 cm height which have some positive effects, e.g., trapping water, especially if the ridges are tied, but have many detrimental effects on crops and the environment (Bunderson et al., 2017). The raised ridges are also labour intensive to construct yearly which calls for more labour reducing and soil conserving technologies such as Conservation Agriculture (CA) where ridges are not constructed annually but maintained from one season to the next (Thierfelder et al., 2016a).

Conservation Agriculture is a cropping system based on minimum soil disturbance, permanent soil cover using living or dead organic material, and diverse crop associations (FAO, 2012). Several research results have shown that CA improves and stabilizes crop yields (Madembo et al., 2020; Thierfelder et al., 2015), conserves soil and water resources (Page et al., 2020; Thierfelder & Wall, 2009), increases biodiversity (Mhlanga et al., 2020; Muoni et al., 2019), reduces some greenhouse gas emissions (O'Dell et al., 2020; Page et al., 2020) while potentially maintaining or increasing soil carbon (Ligowe et al., 2017; Powlson et al., 2016). Improving grain yield is an associated longer-term benefit with the proper implementation of CA (Thierfelder et al., 2015). Although, CA systems have potential to improve yields, good agronomic practices including early planting, weed control and selection of suitable varieties is crucial. Maize varieties [hybrids and open pollinated varieties (OPVs)] have been assessed in several studies across Southern Africa e.g., Hlatywayo et al., (2016) and Thierfelder et al., (2016b). Farmers' preferences on the varieties to grow vary. For example, in Mozambique smallholder farmers preferred short season varieties such as ZM 309 which is an OPV, because they mature very early hence reducing the risk of complete crop failure (Thierfelder et al., 2016b), whereas in other areas hybrids have been the most preferred and used type of germplasm. Additionally, incorporating legume-based crop rotations or intercropping under CA has been demonstrated to not only enhance total system protein and total system energy in Zambia's smallholder farmers' households, have similar climatic conditions with Malawi smallholder farmers, (Mhlanga et al., 2021) but also contribute to crop diversification, thereby improving dietary diversity through valuable nutrients such as protein, vitamins, iron, and zinc obtained from the legumes (Bassett et al., 2010; Scalbert et al., 2005; Stroehle et al., 2006).

Since different types of crops grown in diversified systems have different nutritional composition, it is important to quantify the overall contribution of involved crops. Research on the contribution of different crops, crop management, and environmental conditions on crop productivity in smallholder farms in Southern Africa has been done but mainly focusing on individual crop grain yields and not much on nutrition of involved crops. In studies where these aspects were investigated, it was usually individually or combined depending on the aim. Thus, our study seeks to address how diversified systems under CA systems contribute to human nutrition in different environments. The aim of this paper was therefore to assess if: a) G × M interaction influence productivity with specific emphasis on human nutrition, and b) maize-legume systems under CA may improve the nutritional yield of a household. The specific objective of the study was to evaluate the effect of different cropping systems under conventional practice and no-tillage on maize and legume grain yields, total system protein and total system energy in Central and Southern Malawi smallholder farming systems. However, here we try to address these objectives by evaluating the effect of improved varieties on yield productivity, total system protein and total system energy under different cropping systems in Malawi.

2 Methods

2.1 Study area

The study was conducted in on-farm sites located in Central and Southern Malawi from 2005/2006 to 2018/2019 cropping seasons (Table 1). Sites in Central Malawi and Southern Malawi received 368 – 1863 mm of rainfall in

Table 1 Geographical location, altitude, and soil type in the ten targeted sites in central and southern Malawi

	District	Site name	Latitude[b]	Longitude[b]	Altitude (masl)[b]	Soil type[b]
Central Malawi	Nkhotakota	Zidyana	-13.23	34.26	514	Lixisols
		Mwansambo	-13.29	34.13	660	Lixisols
		Linga	-12.80	34.20	491	Lixisols
	Salima	Chinguluwe	-13.69	34.24	653	Lixisols
	Dowa	Chipeni	-13.76	34.05	1164	Luvisols
Southern Malawi	Balaka	Lemu	-14.78	35.03	687	Luvisols
		Malula	-14.96	34.99	613	Luvisols
		Herbert	-14.88	35.05	635	Luvisols
	Machinga	Matandika	-15.18	35.28	683	Luvisols
	Zomba	Songani	-15.29	31.45	815	Lixisols

[b] source: Komarek et al. (2021)

a unimodal pattern during the study period. The cropping seasons started in November and ended in April in a normal season. Maize (*Zea mays* L.) and to a certain extent cassava (*Manihot esculenta* Crantz) are among the common crops grown across the study sites (communities) namely Zidyana, Mwansambo, Linga, Chinguluwe, Chipeni, Lemu, Malula, Herbert, Matandika, and Songani located in Central and Southern Malawi. We maintained the same farmers' fields throughout the study period, even after the death of the hosting farmer. The soils of the sites can be generally clustered as *Luvisols* and *Lixisols* with site-specific variations. Some farmers in the study sites practice crop rotations (especially in Central Malawi) but the majority use intercropping (in Southern Malawi) as diversification strategy involving grain legumes such as groundnut, cowpea and pigeon pea, amongst other species. These sites were selected to represent the climatic and economic conditions of the different agro-ecological zones of Malawi; thus, the findings of the study could be broadened to different parts of the country and similar environments elsewhere.

2.2 Experimental design

The experimental design was a randomized complete block design (RCBD), with three main treatments. All treatments were replicated by 6 farmers at each study site during each cropping season. Replication by multiple farmers and across different seasons helped increase the robustness and reliability of the experimental results, providing a more comprehensive understanding of the impact of the treatments under various conditions. All sites had maize as the main crop from the onset. From cropping season 2012/2013, crop rotations were practiced in all treatments. The descriptions of the treatments were as follows:

a) Conventional practice (CP) – maize was grown on ridges and furrows that were constructed in each season. No residues were retained.
b) No tillage (NT) – sole maize crops grown under minimum soil disturbance on old ridges which subsided and were never reformed. Dibble sticks were used to make holes to place fertilizer and seed separately. Crop residues were retained on the soil surface at a rate of approximately 2.5 t ha^{-1}.
c) Conservation agriculture (CA) – maize crops grown under minimum soil disturbance on old ridges which subsided and were never reformed. Crop residues were retained on the soil surface at a rate of approximately 2.5 t ha^{-1}. Maize was intercropped with a legume.

We deliberately labelled NT and CA differently although we acknowledge that even though the NT systems were fully rotated from 2012/2013 onwards and could be labelled CA according to the FAO definition. But for ease of distinguishing from the intercropped CA system, we labelled them as described above. In Central Malawi, the legume used in the intercrops was cowpea and the rotational legume was groundnut. In Southern Malawi pigeon pea was the companion crop of maize in intercrops (except for Herbert which had a maize cowpea intercropping). The rotation legumes were pigeon pea in Malula, Matandika and Songani; cowpea in Herbert and groundnut in Lemu. The seeding rate for pigeon pea was 25 kg ha^{-1}, and 80 kg ha^{-1} for cowpea and groundnut. The plots were subdivided into five equal portions in which five different maize genotypes were grown at each farmer's field in each season (Table 2). The plots used had similar management in the previous five years and the most common crop was maize under conventional ploughing practices. The maize varieties that were grown during the study period had different maturity lengths and were either stress tolerant (heat and water) or non-stress tolerant. We used hybrids as well as open pollinated varieties (OPVs) in varietal comparison. Non-drought tolerant varieties were grown from the beginning of the experiments and drought tolerant varieties were introduced during the 2013/2014 cropping season. The improved hybrid varieties were SC

Table 2 The maize varieties grown at different sites during the study period

Sites	Maize variety										
	DKC 8033	DKC 8053	DKC 9053	DKC 9089	MH 30	MH 31	PAN 53	SC 627	SC 719	ZM 309	ZM 523
Chinguluwe	n	y	y	y	y	n	y	y	y	n	y
Chipeni	y	y	y	y	y	y	y	y	y	n	y
Herbert	y	y	n	n	y	n	y	n	n	n	y
Lemu	y	y	n	n	y	y	y	n	n	y	y
Linga	n	y	y	n	y	n	y	y	y	n	y
Malula	y	y	n	n	y	y	y	n	n	y	y
Matandika	y	y	n	y	y	y	y	n	y	n	y
Mwansambo	y	y	y	y	y	y	y	y	y	n	y
Songani	y	y	n	y	y	y	y	n	y	n	y
Zidyana	y	y	y	y	y	n	y	y	y	n	y

y means the variety was grown at that site and n means the variety was not grown at that site

719, PAN 53, MH 30 and MH 31 while the open pollinated varieties were ZM 523 and ZM 309. As control variety we use DKC 80–53, one of the most common varieties in Malawi smallholder farms. All maize crops, in intercrops and rotations, were spaced at 75 cm × 25 cm, leaving one plant per station after thinning and gap filling, to achieve a plant population of 53,333 plants ha^{-1}. The same plots and farmer households were maintained at all sites for grain yield measurements throughout the study period inclusive of the period 2005/2006 to 2018/2019.

2.3 Experiment management

The experiments were managed by both farmers and Government of Malawi agricultural extension officers and the regional non-governmental organisation Total LandCare, while CIMMYT researchers provided overall technical supervision. To improve our reach to more farmers, we conducted field days that included field tours at all sites throughout the study period. The overall plot size at each farmers' field was 3000 m^2, which was subdivided into three treatments of 1000 m^2 each. All plots were planted after the first effective rains of the season i.e., after receiving at least 30 mm of rainfall within two days from the 15th of November. All treatments (except the legumes in the intercrop) received the same basal dressing at 69 kg ha^{-1} (21 kg ha^{-1} N: 21 kg ha^{-1} P_2O_5: 4 kg ha^{-1} S) application rate. Top dressing was done to maize only using urea (46% N) at 100 kg ha^{-1} application rate approximately three weeks after sowing.

Crop rotations of maize and legumes in all treatments were introduced from the 2012/2013 cropping season in Zidyana, Mwansambo and Chipeni and 2013/2014 cropping season in Songani, Matandika, Malula, Linga, Lemu, Herbert and Chipeni. Crop rotations were practiced with both maize and legume phases in each cropping season at each site. Farmers in Herbert showed little interest in pigeon pea due to limited selling options and opted for cowpeas instead. Groundnut was spaced at 37.5 cm between rows and 20 cm between plants in both rotations and intercropping with maize. Pigeon pea was spaced at 75 cm × 20 cm with 1 seed per planting station after thinning in CA rotations, while in intercrops it was spaced at 50 cm between plants and the rows were located between the maize rows. Cowpea rows were between maize rows and the in-row spacing was 40 cm and as sole crops (Herbert) they were planted at 37.5 cm × 40 cm spacing.

Weed control in NT and CA treatments was done using glyphosate [*N*-(phosphonomethyl) glycine] at 2.5 L ha^{-1} (1.025 L ha^{-1} active ingredient) and bullet [25.4% Alachlor (2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl) acetamide) at 6 L ha^{-1}) depending on cropping seasons. In later years, bullet was replaced by the more environmentally benign product Harness® (acetochlor (2-ethyl-6- methylphenyl-d11)) which was applied in all communities from 2017 cropping season, at 1 L ha^{-1} application rate. Hand hoes were used to control weeds which emerged as the season progressed. Weed control in CP treatment was done through tillage and later using hand hoes whenever necessary.

Harvesting of maize was done at physiological maturity by measuring total cob fresh weight at 10 sampling plots of 7.5 m^2 (5 m × 2 rows), avoiding borders, and a subsample of 20 cobs was collected for further drying of the cobs from the beginning of the experiments to the 2011/2012 cropping season. From the 2012/2013 cropping season onwards, only two samples were collected from each variety across the treatments (each sampling point measured 5 m × 2 rows). The subsample collected had only 4 cobs. Legume crops were also harvested from 10 sampling points with similar land area as maize. Each sampling point measured 5 m × 4 rows). A pod-sub-sample of approximately 2 kg was collected for further drying. The sub-samples were air-dried and their dry weights and grain moisture were collected which were used to calculate maize and legume yields in kg ha^{-1} at 12.5% and 9% moisture basis for maize and legumes, respectively.

2.4 Calculations

Since some of the cropping systems in our study involved different crops and different crop sequences and spatial arrangement, it was important to express the systems productivity in terms of a common unit for the possibility of comparisons. To do this, we expressed system productivity in terms of total system protein (kg ha^{-1}) and total system energy (gigajoules (GJ) ha^{-1}). The total system protein was calculated based on nutritive values of maize, groundnut, cowpea and pigeon pea obtained from the Food Nutrition Table (http://www.foodnutritiontable.com/). The protein percentage used for calculations for maize, cowpea, groundnut and pigeon was 10%, 28%, 26% and 22% respectively. In intercrops, total system protein was determined by adding the protein yield from maize and the legume. The total system energy calculations were based on crop energy values obtained from the GeNUS database (http://projects.iq.harvard.edu/pha/genus). Total system yield was calculated using the formulas shown in Table 3. Differences in the formulae for calculating GJ are due to different cropping systems (intercrop or rotations) and different crop combinations. See Komarek et al. (2021) and Mhlanga et al. (2021) for further explanation.

2.5 Statistical analysis

The grain yields of crops (legumes and maize), total system protein, and total system energy were subjected to a normality and homoscedasticity test in R environment before analysis (R Core Team, 2021). Since on-farm data is usually of hierarchical nature and hence non-independent, the use of linear mixed models was more desirable in assessing the effect of treatment and variety (fixed factors) on the investigated aspects. In the models, cropping seasons and farmers nested into the sites were treated as random factors to account for repeated measurements and grouping factors (Eq. 1).

$$\gamma_{\mathrm{ijk}} = \mu + \alpha_{\mathrm{i}} + \tau_{\mathrm{j}} + (\alpha\tau)_{\mathrm{ij}} + \varepsilon_{\mathrm{ijk}} \tag{1}$$

where γijk is the maize/legume grain yield, system energy, and protein yield observed in the k$^{\text{th}}$ site of the i$^{\text{th}}$ variety in the j$^{\text{th}}$ treatment (i = 1, 2, …,; j = 1, 2, …,; k = 1, 2, …); μ is the grand mean; αi is the effect of the i$^{\text{th}}$ variety; τj is the effect of the j$^{\text{th}}$ treatment; (ατ) ij is the interaction effect of the i$^{\text{th}}$ variety with the j$^{\text{th}}$ treatment; and εijk is the random error.

The rotation factor was tested by separating the data sets before and after introduction of crop rotations on all communities. Wald Chi-squares were used to test the significance of the fixed factors and their interactions using “lme4” package in R (Bates et al., 2014). Mean separation of all significant data was done using Tukey test in “emmeans” package in R (Lenth et al., 2018).

3 Results

3.1 Maize grain yield

Treatments and varieties had a significant effect on maize grain yield (Table 4). Treatment × variety interaction had a significant effect on maize grain yield after introduction of crop rotations. Conventional practice treatment had lower maize grain yields across varieties compared to CA and NT treatments (Fig. 1). The yield benefits of NT and CA when compared to CP ranged between approximately -35 to 240%. The overall mean yield was approximately 4000 kg ha^{-1}. The OPVs ZM 309 and ZM 523 and the hybrid MH 31 were below the average yield irrespective of the cropping system. Both OPVs and hybrids showed clear yield gains in CA and NT when compared with CP.

Table 3 The formulas used in the calculation of system yield for each cropping system

Treatment	System yield (GJ ha^{-1})
Conventional Practice (CP) maize without legume rotation	(MzY × MzKcal × 10)/GJConv
Conventional Practice (CP) maize with legume rotation	(½ × MzY × MzKcal × 10 + ½ × LegY × LegKcal × 10) /GJConv
No-tillage (NT) maize without legume rotation	(MzY × MzKcal × 10)/GJConv
No-tillage (NT) maize with legume rotation	(½ × MzY × MzKcal × 10 + ½ × LegY × LegKcal × 10) /GJConv
Conservation Agriculture (CA) maize legume intercrop without legume rotation	(MzY × MzKcal × 10 + LegY × LegKcal × 10) /GJConv
Conservation Agriculture (CA) maize legume intercrop with legume rotation	(½ × (MzY × MzKcal × 10 + LegY × LegKcal × 10) + ½ × (LegY × LegKcal)) /GJConv

MzY and LegY = maize grain yield and legume grain yield in kg ha^{-1}, respectively; MzKcal and LegKcal = kcal/100 g seed for maize and legume crops, respectively; GJConv is a conversion factor that converts kcal to GJ, where 1 GJ is 238845.897 kilocalories.

Table 4 Linear mixed effects model output for maize grain yield, total system energy and total system protein

Maize grain yield									
Source	Combined effect			No rotations			With rotations		
	Df	Wald chi-square	*P*-value	Df	Wald chi-square	*P*-value	Df	Wald chi-square	*P*-value
Treatment (T)	2	632.4	$<2.20\times10^{-16}$***	2	155.4	$<2.20\times10^{-16}$***	2	331.4	$<2.20\times10^{-16}$***
Variety (V)	10	435.9	$<2.20\times10^{-16}$***	3	79.19	$<2.20\times10^{-16}$***	9	335.9	$<2.20\times10^{-16}$***
T×V	20	54.7	4.50×10^{-04}**	6	3.97	0.68	18	31.2	0.03*
Total system energy									
	Combined effect			No rotations			With rotations		
	Df	Wald chi-square	*P*-value	Df	Wald chi-square	*P*-value	Df	Wald chi-square	*P*-value
Treatment (T)	2	1870.2	$<2.20\times10^{-16}$***	2	293.0	$<2.20\times10^{-16}$***	2	2418.9	$<2.20\times10^{-16}$***
Variety (V)	10	265.8	$<2.20\times10^{-16}$***	3	4.44	0.22	9	206.85	$<2.20\times10^{-16}$***
T×V	20	44	0.001**	6	20.01	0.002656 **	18	54.1	$1.792e^{-05}$ ***
Total system protein									
	Combined effect			No rotations			With rotations		
	Df	Wald chi-square	*P*-value	Df	Wald chi-square	*P*-value	Df	Wald chi-square	*P*-value
Treatment (T)	2	2602.5	$<2.20\times10^{-16}$***	2	293.0	$<2.20\times10^{-16}$***	2	2418.9	$<2.20\times10^{-16}$***
Variety (V)	10	183.4	$<2.20\times10^{-16}$***	3	4.44	0.22	9	206.85	$<2.20\times10^{-16}$***
T×V	20	61.3	4.51×10^{-06}***	6	20.1	0.002656 **	18	54.1	1.792×10^{-05} ***

P-values were significant at *** $P<0.001$, ** $P<0.01$, * $P<0.05$

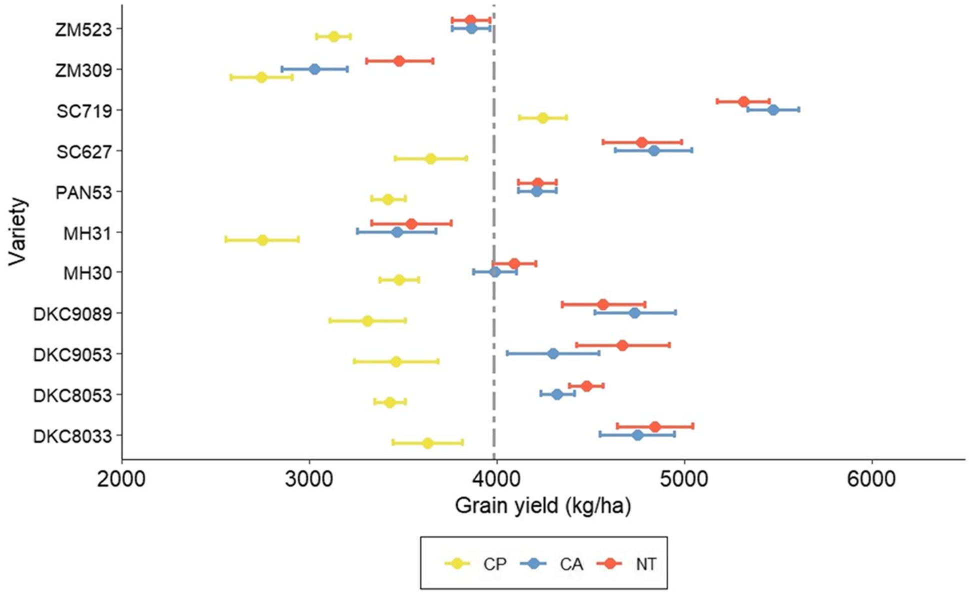


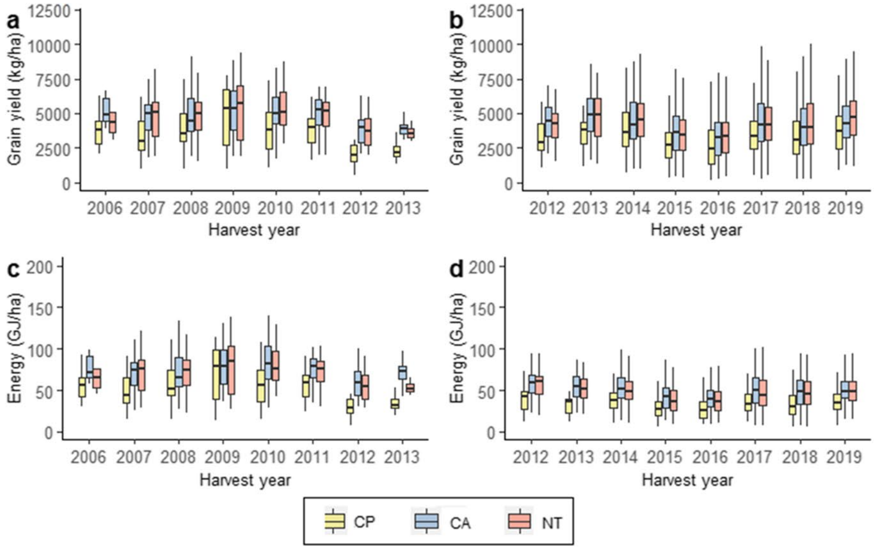
Fig. 1 Interactive effect of treatments and varieties on maize grain yield across 13 cropping seasons at study sites in central and southern Malawi. Treatment abbreviations: CP – conventional practice involving construction of ridges, NT- no-tillage system which involved seeding into old ridges without remaking them plus retention of crop residues and, CA – no-tillage with residue retention and intercropping. The vertical dotted line shows the overall mean. Description of varieties are provided in Komarek et al., 2021

Highest maize yield was observed in the long-season hybrid maize variety SC 719 (5635 kg ha^{-1}) under CA treatments.

The results also show that introduction of crop rotations across sites resulted in significant treatment × variety interaction (Table 4). Yields under CA and NT were higher than CP before and after introduction of crop rotations, however maize yield after introduction of rotations were lower than before rotations (Fig. 2).

3.2 Legume grain yield

Treatments and treatments × rotational crop interaction had a significant effect on legume grain yield (Fig. 3). Crop yields observed under CP treatments were significantly lower than CA and NT treatments throughout the study period.



Treatment	Grain yield (kg/ha)	
	No rotations	Rotations
CP	3505b	3445b
CA	4709a	4303a
NT	4647a	4398a

Treatment	Energy (GJ/ha)	
	No rotations	Rotations
CP	51.8b	33.6c
CA	73.1a	48.3a
NT	68.7b	46.7b

Fig. 2 Maize grain yield: **a** before introduction of rotations and **b**) after introduction of rotations. Total system energy: **c** before introduction of rotations and **d**) after introduction of rotations. Treatment abbreviations: CP – conventional practice involving construction of ridges, NT- no-tillage system which involved shaping the ridges without remaking them plus retention of crop residues and, CA – no-tillage with residue retention and crop rotation/ intercropping. Different letters on mean maize yield show treatments that are significantly different from each other at 5% probability level

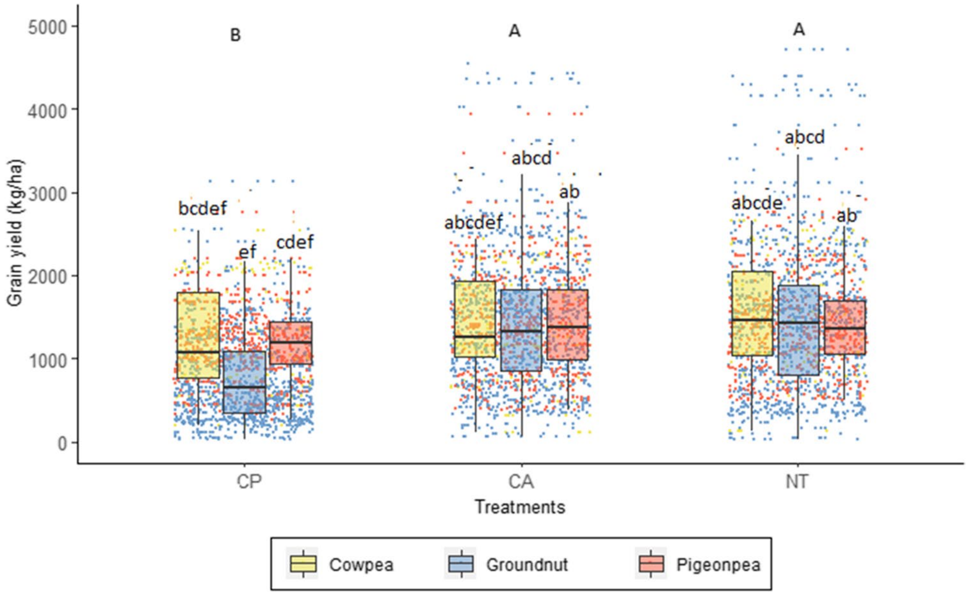


Fig. 3 Crop and treatment interaction effects on legume grain yields from 2006 to 2019 cropping seasons at the study sites. Treatment abbreviations: CP – conventional practice involving construction of ridges, NT- no-tillage system which involved shaping the ridges without remaking them plus retention of crop residues and, CA – no-tillage with residue retention and crop rotation/ intercropping. Different lower cases above the box-plots indicant significantly different legume crop yields and different upper cases indicate significantly different treatments

3.3 Total system protein

Combined results show that treatments, varieties, and their interactions had a significant effect on total system protein (Table 4). Conventional practice treatments had significantly lower total system protein ranging between, 245 to 327 kg ha^{-1}, than CA and NT treatments (range 385–477 kg ha^{-1} and 351–419 kg ha^{-1}, respectively) (Fig. 4). Also, systems that involved legumes and OPVs (ZM 309 and ZM 523) had lower total system protein than other varieties across treatments (Fig. 4). Conservation agriculture treatment involving rotation of grain legumes with maize/legume intercrops had the highest protein yield. No-till treatment had higher total system protein than CP treatments even before introduction of crop rotations (Fig. 5).

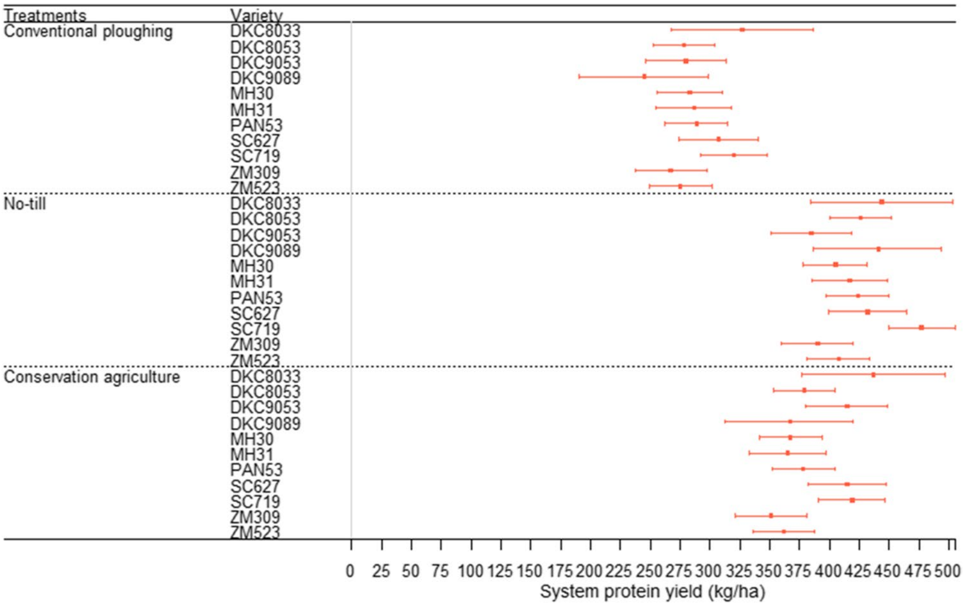
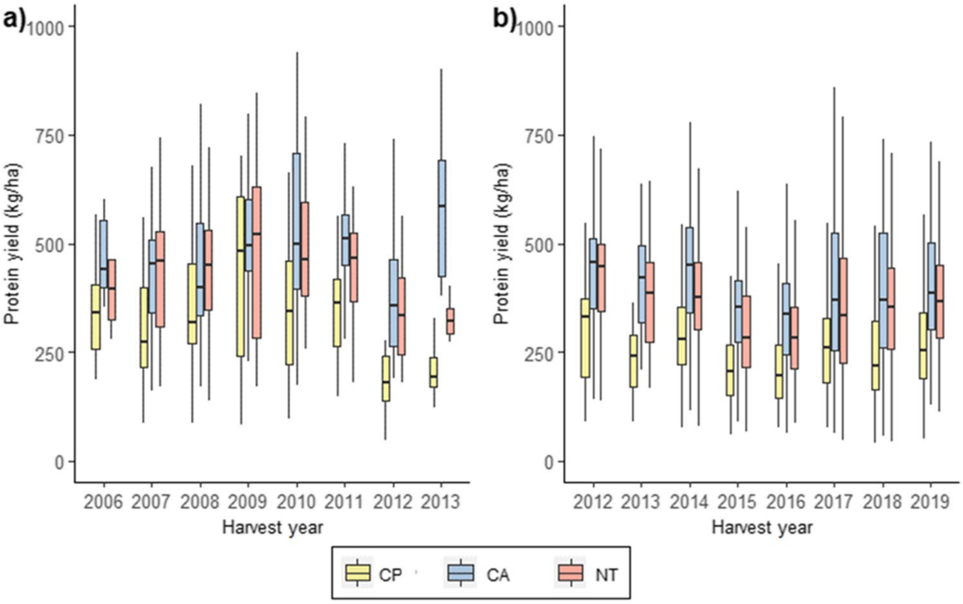


Fig. 4 Effect of treatments and varieties on total system protein yield across 13 cropping seasons at study sites in central and southern Malawi. Treatment abbreviations: CP – conventional practice involving construction of ridges, NT- no-tillage system which involved shaping the ridges without remaking them plus retention of crop residues and, CA – no-tillage with residue retention and crop rotation/ intercropping. Description of varieties are provided in the materials and methods. The dots show the system protein yield mean and the whisker show the 95% confident intervals



Treatment	Protein yield (kg/ha)	
	No rotations	Rotation
CP	249c	316c
CA	382a	476a
NT	351b	419b

Fig. 5 Total system protein; **a** before introduction of rotations and **b**) after introduction of rotations. Treatment abbreviations: CP – conventional practice involving construction of ridges, NT- no-tillage system which involved shaping the ridges without remaking them plus retention of crop residues and, CA – no-tillage with residue retention and crop rotation/ intercropping. Different letters above the box-plots indicant significantly different treatments. Different letters on mean yield show treatments that are significantly different from each other at 5% probability level

3.4 Total system energy

Overall, the results show that treatments, varieties, and their interactions had a significant effect on total system energy (Table 4). The total system energy ranged between 41.0—66.0 GJ ha^{-1} across the treatments (Fig. 2). Before introduction of crop rotations, the interaction of treatments and varieties had a significant effect total system energy (Table 4). Conservation agriculture and NT treatments had higher total system energy than CP. After introduction of crop rotations, treatment, variety and their interactions had a significant effect on total system energy and as observed in no rotations, CP treatments had significantly lower total system energy than CA and NT (Fig. 2). Variation of total system energy was observed across seasons. Under CA, the highest system energy was observed with DKC 9053 variety while DKC 8053 and DKC 9053 had highest total system energy under CP (Fig. 6).

4 Discussion

Improving food and nutrition security in smallholder farms in Central and Southern Malawi remains a key challenge due to several factors including poor management practices, mono-cropping, using saved seed, and climate related shocks. We examined how management practices (CP, NT with rotations of maize and grain legumes, and full CA systems involving no-till and rotation of maize/legume intercrop with sole grain legumes), and varieties influenced maize and legume grain yield, total system protein and total system energy in central and Southern Malawi smallholder farms. The approach to assess the impact of cropping systems using total system protein and total system energy has been previously shown under CA in Eastern Zambia e.g., Mhlanga et al. (2021) and in Malawi Komarek et al. (2021). Total system protein and energy was higher under CA than CP in Zambia and Malawi smallholder farms. We used a similar approach in both studies but enhancing the analysis to also show effect of maize varieties on overall productivity and its interaction with crop management. Our study highlights important cropping systems that have potential to reduce food and nutrition insecurity, however most smallholder farmers have limited resources that might hinder them to adopt the cropping systems. To ensure the study is relevant in smallholder farms in Malawi we conducted it at on-farm sites, and it was managed by both farmers and researcher. Farmers were responsible for all agronomic practices including weed management, fertilizer application and pest control; following advices from researchers. Hence, this set-up (a real-world) allows us to conclude the cropping systems tested in this study are both feasible and attainable in smallholder farms.

4.1 Maize and legume grain yields

Conventional practices had lower yields when compared to NT and CA systems. No till and CA treatments had higher yields than CP due to addition of crop residues. Retention of crop residues enhance water infiltration and retention in the soil. This is important during the prolonged dry spells that are commonly experienced in the study sites. Conventional practices based on ridge tillage have several detrimental effects including high soil, water and nutrient losses (Bunderson et al., 2017; Thierfelder et al., 2016a) hence lower crop yields are obtained in these systems under the Malawian context. Ploughing disrupts soil structure and natural ecosystem that contributes to soil fertility decline. Also limited crop residue retention and soil fertility amendment reduces soil organic matter content, hence crop yields decline in this system. Rickson et al. (2015) reported that decline in soil organic matter content reduces nutrient retention, which has a negative effect on crop yields. The CA treatment had slightly higher maize yields, which were slightly higher than in NT treatment. This might be due to the fact that a legume in a maize intercrop system enhances soil fertility build-up through biological nitrogen fixation (BNF) and addition of organic matter that increase the maize

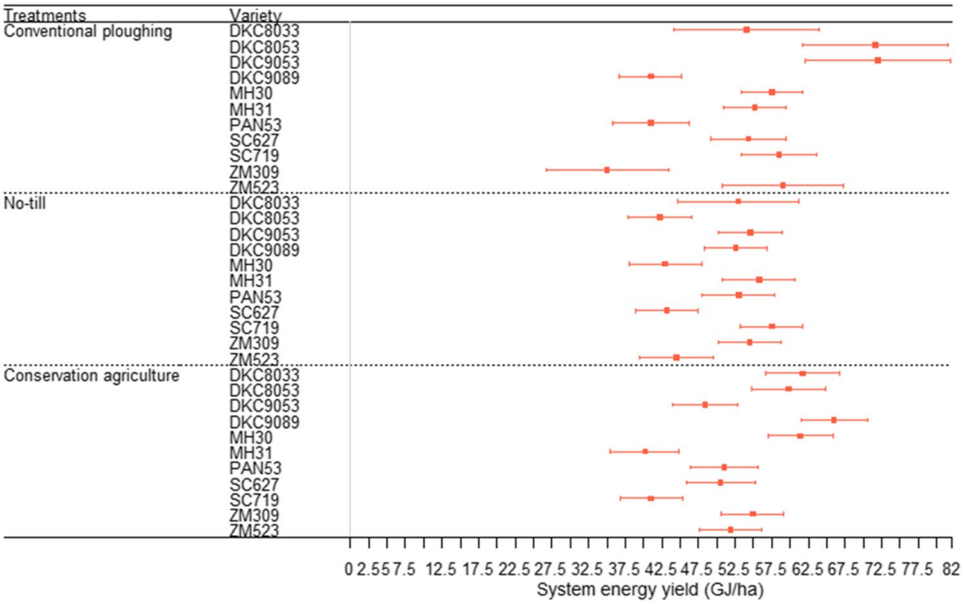


Fig. 6 Effect of treatments and varieties on total system energy across 13 cropping seasons at study sites in central and southern Malawi. Treatment abbreviations: CP – conventional practice involving construction of ridges, NT- no-tillage system which involved shaping the ridges without remaking them plus retention of crop residues and, CA – no-tillage with residue retention and crop rotation/ intercropping. Description of varieties are provided in the materials and methods. The dots show the system energy yield mean and the whisker show the 95% confident intervals

yields (Vanlauwe et al., 2019). Maize yields in NT were higher than CP before introduction of crop rotations involving grain legumes. These results agree with Mupangwa et al. (2019) and Michael et al. (2021), who reported that application of 30–80 kg N ha^{-1}, under NT and retention of crop residues (2—5 t ha^{-1}) increased the maize grain yields under good agronomic practices. However, there is a potential nitrogen (N) lock-up problem in this system (Michael et al., 2021) if no-tillage with crop residues are practiced without integration of leguminous crops (Gentile et al., 2011). This explains why introduction of crop rotations with grain legumes in CA and NT overall improved maize yields as the additional N from the legumes eased N lockup in the studied soils. Maize yield in NT was higher after introduction of the rotational crop than CA because the more diversified CA system had a competing companion crop, which resulted in a slight depression of yield. In addition, growing a leguminous intercrop in CA meant that the row spacing in CA had to be widened from 75 to 90 cm to allow the legume to proliferate. Maize could not compensate for this, hence yields in CA where overall lower after introducing rotations as compared to NT.

Crop rotations have several advantages to the cropping system including increasing soil organic carbon (SOC) and reducing pests, diseases and weed pressure which gives crops a competitive advantage (Sapkota et al., 2017; Thierfelder et al., 2013; Weisberger et al., 2019). Previous studies have shown that increasing crop diversity suppresses weeds more in NT and CA systems than CP practices (Lee & Thierfelder, 2017; Nichols et al., 2015), this could help explain why CP yields were still low even when crop rotations were practiced (Weisberger et al., 2019). Also after 13 years of good agronomic practices, there is a build-up of organic matter in the soil which improves soil quality in the CA and NT systems whereas in the CP (Hussain et al., 2021), decomposition is high due to increased contact between active microbial populations and crop residues, and less build-up takes place (Ni et al., 2016). In this current study, CP was subjected to drastic soil disturbance as ridges are annually split and rebuild in the furrow which is the traditional practice in Malawi (Bunderson et al., 2017). This not only leads to destruction of the pore system but also enhances oxygen intake into the subsurface leading to faster decomposition (Lupwayi et al., 2004). Higher yields under CA and NT could also be related to less disturbance of soil macro and micro-organisms that enhances the ecological benefits and soil water properties including soil moisture content and soil water infiltration (Mhlanga & Thierfelder, 2021; Muoni et al., 2019).

Varieties showed significant effect on maize grain yield. This could be due to differences among yield potentials of the varieties which are associated with their genetic makeup. No-till and CA systems with crop residue retention reduce soil temperature which encourages root growth, nutrient, and water uptake as compared to CP (Hlatywayo et al., 2016). Open pollinated varieties ZM 309 and ZM 523 had lower yields than hybrids as expected. However, OPVs have been reported to be more stable than hybrids and suit smallholder farmers who struggle to purchase seed every season (Lana et al., 2017). Unlike hybrids, OPVs can be recycled for 3–4 cropping seasons without major yield penalty. In these trials, replacement of varieties with improved ones were done to maintain the genetic gains that are associated with release of improved varieties; however, each community had the same variety per season. To address the errors that arise due to changes in the varieties, management practices and legume crops, locations were included as a random factor in our analysis (Schielzeth et al., 2020).

CA and NT had higher legume grain yields than CP. Several reasons could contribute to this: a) as CA systems are planted on the flat and are not restricted to the ridge and 75 cm row spacing, they can be planted at optimal plant population, covering the whole available soil area. In these trials, legumes were planted at 37.5 cm rows which exploited the available soil area much more efficiently than planting under CP. In addition, improved conservation of resources in CA systems, as well as increased BNF under such cropping systems (Torabian et al., 2019) may increase legume yields. In summary, a higher plant population, increased BNF combined with high moisture conservation and improved biological activity resulted in higher legume grain yield in CA and NT when compared to CP.

4.2 Total system energy and protein

Total system energy was higher in CA and NT treatments compared to CP treatments. This might be due to minimum soil disturbance and retention of crop residues under these systems that helps with moisture and soil conservation, as well as improved soil and biological activity (Mhlanga et al., 2020; Muoni et al., 2019; Thierfelder & Wall, 2009). With increased total system energy in smallholder farms, farmers have opportunity to diversify their food production by growing a wider range of crops that contributes to a more balanced and nutritious diet for their households. This further results in a more diverse and resilient agricultural system that can withstand the impacts of climate change, thus CA and NT have potential to alleviate food and nutrition insecurity in Malawi smallholder farms. The CA treatment had an additional benefit of the legumes that were grown as intercrops that also contributed to the total system energy. There was no clear pattern of cropping systems and varieties on total system energy. However, the total system energy was at least 30 GJ ha^{-1}, which is expected to meet the basic caloric requirements per household per year (Harttgen & Klasen, 2012). Hence, improved varieties plus improved management practices have potential to alleviate food security challenges faced by smallholder farmers.

Overall, NT and CA systems had high protein yield when compared to CP systems. This could be related to higher crop yields obtained in these systems than under CP. Maize grain has approximately 10% protein. The CA treatments which included grain legumes had better protein yield because grain legumes are a rich source of proteins (Watson et al., 2017). This suggests CA systems results in high protein production that contributes to better overall health outcomes and reduce the risk of malnutrition in smallholder farmers' households. In this study, we observed increased total system protein yield across treatments after introduction of crop rotations with grain legumes. Higher protein yield was observed under CA where maize/legume intercrop was rotated with maize. Hence, increasing crop diversity in smallholder farming systems, coupled with minimum soil disturbance and retention of crop residues makes the system more nutritious.

5 Conclusions

Improved agricultural practices that enhance crop yields, total system energy and protein are crucial in Malawi smallholder farms. Here we studied the contribution of improved varieties and cropping systems to maize and legume grain yield, protein yield, and total system energy. Conservation agriculture, particularly minimum tillage and crop rotations of maize and grain legumes, significantly enhances productivity in smallholder farms in Malawi. The adoption of NT and CA systems leads to higher maize and legume yields compared to CP. Furthermore, incorporating more diverse cropping systems, such as intercropping maize with legumes, improves overall nutrition. While maize varieties, including hybrids and OPVs, perform differently across treatments, emphasizing the adoption of improved varieties alongside advanced cropping systems like CA is essential for sustainable smallholder farming. We recommend farmers to utilize energy gains to invest in practices that increases the resilience of their agricultural systems to climate change. These practices include diversifying their cropping systems by growing a wider range of crops that contributes to a more balanced and nutritious diet for their households.

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Data availability The data will be made available upon reasonable request to the authors.

Declarations

Conflict of interest We declare that there is no conflict of interest with our study.

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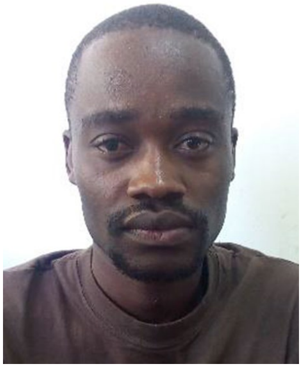

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