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Marginal more than mesic sites benefit from groundnut diversification of maize: Increased yield, protein, stability, and profits

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ABSTRACT

Sustainable Intensification (SI) interventions are urgently required, particularly those suited to resource poor farms in Africa. Legume crops have been promoted as a key ingredient for SI of rainfed grain production on smallholder farms, with variable results. There is a need to explore the extent to which legume diversification of maize production impacts stability, nutrition, and income. This is particularly so for marginal environments. On-farm experimentation was conducted in Central Malawi over two to seven years on 29 farm sites (120 year-site combinations). The farms were located within four areas that included lakeshore, dissected hills (two locations) and upland plain. Maize diversification included a long-duration legume pigeonpea and a medium duration legume groundnut, grown in rotation or intercropped with maize, and as a doubled-up legume rotation (DLR). To quantify the performance of systems under low, medium, and high yield environments, we used long-term average maize yield to categorize each farm site. All legume diversified systems supported stable grain production in the low yield environment, as shown by 37–41% coefficient of variation for yield, in comparison to 62% for sole maize. The groundnut systems consistently produced the highest grain yield, protein, stable yields, and economic returns, and this performance held up in marginal, low yield environments. In this multi-site, multi-year, on-farm replicated study, the performance of groundnut systems (GnRot and DLR) stood out for high protein (0.529 T ha^{-1} 2 yr^{-1} and 0.615 T ha^{-1} 2 yr^{-1}, respectively over two years) versus unfertilized maize (0.169 T ha^{-1} 2 yr^{-1}). These two groundnut-based systems were produced with half-fertilizer rates compared to sole maize and were economically high performers. However, there was a barrier to adoption of GnRot and DLR in that improved groundnut seed was expensive (USD 157 ha^{-1} 2 yr^{-1}), this initial investment being beyond the means of many farmers, despite the cost largely offset by the generation of high income (USD 1636–1993 ha^{-1} 2 yr^{-1}). Long-term sustainability was assessed by monitoring soil organic carbon (SOC), which was found to be markedly influenced by soil texture (sites with SOC >1.5% had sand content <50%). Legume diversification effects on SOC were not discerned, possibly due to high sand content on the oldest trial sites. This study highlights the value of longitudinal data and including a wide range of soil texture sites in on-farm experimentation to identify overall legume diversification effects within maize systems.

1. Introduction

Farmers in East and Southern Africa face multiple challenges in the form of poor soil fertility and high climate variability, as well as limited investment in infrastructure and education (Ellis et al., 2003). Malawi's small-scale farming sector is typical of the region, with poverty, chronic food insecurity and high reliance on rain-fed production of maize (Bezner Kerr et al., 2019). Sustainable intensification (SI) has been put forward as a pathway to improve agricultural production for food and income, while simultaneously protecting the environment and conserving resources (Smith et al., 2016; Snapp et al., 2018). Agricultural system underperformance is becoming even more acute as temperatures rise and rainfall patterns alter in Southern Africa (Funk et al., 2018). This highlights the importance of systematic assessment of SI systems that perform well in marginal environments and that are adoptable by resource-limited farmers (Morgan et al., 2019).

Malawi has been heralded as a successful example of large-scale

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Abbreviations

SI	Sustainable Intensification
Yr	Year
ha	Hectare
Mz0	Maize unfertilized
MzNP	Maize fertilized
DLR	Doubled up legume pigeonpea intercropped with groundnut and rotated with maize
GnRot	Groundnuts with maize rotation
PpRot	Pigeonpea with maize rotation
MzPp	Maize and pigeonpea intercrop
T ha^{-1} $2yr^{-1}$	Yield in tons per hectare over two years

productivity gains achievable through government investment in access to fertilizer and maize seed (Dorward and Chirwa, 2011). The evidence for yield gains is, however, disputed (Messina et al., 2017). Further, there may be inadvertent negative consequences in the form of drought risk, soil degradation and poor nutrition associated with widespread promotion of intensified maize production (Isaacs et al., 2016). Legume diversification of maize-based smallholder production is an important SI intervention (Beedy et al., 2010; Droppelmann et al., 2017). Yet, there is a body of evidence that grain legume adoption is sporadic and partial in ESA (Snapp et al., 2002), with groundnut (*Arachis hypogaea* L.) and pigeonpea (*Cajanus cajan* (L.) Millsp) being widely cultivated, but primarily on small plots (Mhango et al., 2013). Field experimentation has shown the potential for substantially enhanced land and nutrient use efficiency through diversification with grain legumes; however, studies often involve few sites and limited years of observation (Rusinamhodzi et al., 2012; Silberg et al., 2017). Evidence is needed to better understand where legume crops are suited to grow, and where they best support SI.

A research gap exists around grain legumes performance in marginal environments and on sites with poor agronomic management. The value of longitudinal study is illustrated by Waddington et al. (2007a) who showed that groundnut-maize rotation sequences in Zimbabwe on sandy, marginal farm sites produced very low groundnut yields, and modest gains in maize rotations relative to continuous maize. At the same time, yield gains through groundnut rotations did persist for over a decade. In Kenya, groundnut intercropped with maize enhanced productivity substantially at some sites but not others, with an important interaction shown for an indicator of degraded soils, the presence of the parasitic weed Striga *hermonthica* (Oswald et al., 2002). In Central Mozambique, a multi-season on-farm study found that maize intercropped with either pigeonpea or cowpea showed variable, but generally enhanced, grain and economic returns (Rusinamhodzi et al., 2012).

The unique nutritional contributions of legume food crops (Foyer et al., 2016) include high protein at 26% for groundnut and 24% for pigeonpea, compared to maize protein at 9% (Van den Brand, 2011). This shows the potential of pulses to directly addresses SI goals for improved family nutrition; thus, protein content is becoming recognized as an indicator of SI performance (Grabowski et al., 2018). Yet, there have been few studies of the specific contributions of legume diversification to protein production on marginal lands and within a smallholder farm context. On-farm experimentation in Malawi has shown the potential for soybean and pigeonpea to substantially enhance protein produced in maize-based cultivation systems (Chimonyo et al., 2019). Yet protein production was completely overlooked in farmer participatory research on legumes in the Congo and Kenya (Muoni et al., 2019), nor was it considered in a recent review of nutritionally-sensitive agriculture interventions (Ruel et al., 2018). The quality of legume protein for human nutrition is also reflected in the amino acid composition, which complements that of maize protein amino acid composition; although anti-nutritional factors associated may require post-harvest processing (Temba et al., 2016).

Another important area of investigation is the effects of grain legumes on soil fertility. Legumes have the potential to build soil nitrogen (N) fertility through biological nitrogen fixation; however, in a pulse legume crop N is removed through grain harvest and the net N gain depends on residue management and above and belowground quantity and quality of residues (Franke et al., 2017). On-farm studies have often focused on yield response, with limited data reported on soil properties response to grain legumes, and interaction with environmental context (Elberling et al., 2003; Kermah et al., 2018). Legume diversification effects on SOC accrual has been especially challenging to quantify. The short to medium term nature of most on-farm trials contribute to limited evidence regarding SOC (Snapp et al., 2010). Long-term trials have shown positive effects of legumes, particularly leguminous trees and shrubs that do not produce grain, where the majority of such studies are conducted on research stations (Beedy et al., 2010; Cong et al., 2015; Hazra et al., 2019). As such, evidence is lacking regarding on-farm soil response to grain legume-diversified cropping systems.

A key question remaining for legume diversification is where should such SI systems be promoted? In particular, legume crops have been promoted for poorer and vulnerable populations, yet rarely has performance been tested under marginal environments (Foyer et al., 2016; Snapp et al., 2019). Performance is more than just yield, and for marginal sites system resilience is very important, thus stability of yield for a range of environments is a key metric (Grabowski et al., 2018). This has been overlooked in many studies, as highlighted by a recent study from Zimbabwe calling for more assessments that include analysis of yield stability (Madembo et al., 2020). The size of the evidence gap is indicated by maize yield being widely used in a recent review, which found that almost all reviewed field experiments relied on this indicator for rain-fed African cropping systems (Droppelmann et al., 2017). Thus, there is a need to analyze cropping system performance that considers multiple dimensions, including soils, yields, protein contribution, stability, and profits.

Given these various dimensions, marginal environments may be defined in multiple ways, with some metrics given more weight than others. For example, as drought is a major concern in much of sub-Saharan Africa, studies on marginality in agriculture focus on low rainfall and high temperatures as the major indicator of a marginal environment (Byerlee and Morris, 1993; Usman et al., 2005). Climate alone however does not fully account for the environmental challenges that smallholder farmers face in managing cropping systems. Other assessments of environmental conditions include a land assessment by Li et al. (2017) where the main parameters for assessing agricultural suitability and thus defining marginal agricultural environments involved properties related to susceptibility of soil to degradation. Previous assessments often faced scale limitations as few were able to account for variability at a fine, site-specific scale; this is due to the coarse resolution of remote-sensed variables (Peter et al., 2018). A site-specific assessment is particularly necessary for smallholder farmers who face heterogeneous conditions given differences in climate, soil, inputs, and socio-economic conditions (Altieri, 2002). Plant breeders have often addressed this issue of accounting for site-specific conditions in identifying appropriate genotypes through using overall mean yields of a site as a proxy indicator for overall environment suitability (Kante et al., 2017; Setimela et al., 2017). Recently this approach has begun to be used in assessing long-term performance of cropping systems as well and could be used for identifying legume performance across a more robust environment metric (Bowles et al., 2020).

Malawi is an interesting case study, based on it being typical of maize-based farming systems in Africa (Blackie et al., 2019). Rural Malawi has a very high population density, thus providing insights into agricultural intensification processes (Jayne et al., 2019). The Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) participatory action research project has been conducted for seven years in Malawi. We conducted purposive selection of sites to represent a range of environments, and extensive baseline characterization to provide context for experimentation (Mungai et al., 2016). The SI assessment framework was applied, with indicators that represent production, economics, human nutrition, and environmental performance (Snapp et al., 2018).

The overall objective of the study was to identify sustainable intensification (SI) interventions for marginal areas, to address in a sustainable manner food security, nutrition, and income requirements among the poorest and most vulnerable. Sustainable intensification based on diversification of maize-based systems was evaluated through on-farm experimentation over two to seven years on 29 sites located in four (Golomoti, Linthipe, Kandeu and Nsipe) extension planning areas (EPAs). Farm sites were categorized as low, medium, and high potential environments based on maize yield potentials across sites. The four research questions addressed were: (1) How does the environment interact with performance in SI systems? (2) Specifically, how does grain yield, biomass, and soil organic matter in maize-based cropping respond to diversification with legumes, for marginal environments? (3) Which SI system is nutritionally superior to other systems in terms of protein produced, and (4) How do SI systems perform economically relative to sole maize?

2. 2. Materials and methods

2.1. Study Sites

On-farm participatory research in Malawi was conducted at 29 sites, from two to seven years (oldest trials started in 2012/2013 season). Farm sites were located in four EPAs in central Malawi, specifically Linthipe, Golomoti, Kandeu and Nsipe (Snapp et al., 2018). The sites represent a range of environments from marginal to mesic sites (Table 1; Fig. 1).

2.2. Trial design

Six cropping systems were evaluated in this on-farm study conducted at 29 sites. An additional treatment of full fertilized sole-maize was included in 13 of the 29 sites. The on-farm experimentation was conducted over two to seven years depending on the site, resulting in 120 year-site combinations. The cropping systems evaluated included two sole maize systems: continuous unfertilized maize (Mz0), continuous full-fertilized maize (MzNP); three 2-year rotation systems with legume crops followed by sole maize fertilized at half rate: groundnut (GnRot), groundnut and pigeonpea intercrop (doubled up legume rotation system = DLR), pigeonpea (PpRot); and maize pigeonpea intercrop (MzPp) (Table 2). A randomized complete block design was used, with three replicates (DLR had three additional replicates at 24 sites). Plot size was 6.75 by 9 m, rows spaced at 0.75 m intervals, each 9 m long. Maize and protein production data has been reported previously for initial years at six of the 29 experimentation sites, see Chimonyo et al. (2019) for full details.

Management followed Malawi recommended agricultural production practices, including plant spacing of 0.75 cm between ridges, prepared by hand hoe and planted with the onset of rains, which generally occurs in late November or early December (Malawi Ministry of Agriculture, 2012). Maize was grown with a within row spacing of 0.25 m, which achieved a plant population density at planting of 53, 000 plants ha^{-1} (Table 2). A modified additive design was used for the intercropped system of maize and pigeonpea, three maize plants per planting station within row were established at 0.90-m spacing between planting stations, resulting in a sowing rate of 44,000 plants ha^{-1} (Chimonyo et al., 2015). The same pattern was used for pigeonpea for a 1:1 maize pigeonpea ratio, for a total of 88,000 plants ha^{-1} in the intercrop (Snapp et al., 2018). For the DLR, GnRot systems, groundnut was planted at a within row spacing of 0.1 m, which achieved a planting density of 133,000 plants ha^{-1}, and pigeon pea population at 44, 000 plants ha^{-1} (Table 2). The full rate of fertilizer used was a basal application of 100 kg NP fertilizer ha^{-1} and top dressing of 100 kg Urea ha^{-1}, to achieve 69 kg N ha^{-1}, 21 kg P ha^{-1} (Table 2). Half rate fertilizer, as a split application with basal and top dressing, was applied to maize in the second year of rotation systems, and half rate fertilizer was applied every year in the MzPp intercrop. No fertilizer was applied to the legume phase in rotations.

2.3. Plant and soil monitoring

Soil samples were taken on the subset of trials still extant (13 out of 29 trials) in July 2018 following the 2017/18 harvest period to evaluate cropping system effects on soil properties. A composite soil sample was taken from each plot at 0–20 cm depth using a soil probe. Samples were air-dried and sieved for processing. Soil properties measured included soil organic carbon (SOC), active carbon (POXC), carbon mineralization (Cmin), and soil texture. SOC was determined using the dry combustion method, active carbon using the permanganate oxidizable carbon (POXC) method (Culman et al., 2012) and one-day carbon mineralization using rewetted soil to 50% water holding capacity method based on Franzluebbers et al. (2000), with slight modifications as described in Culman et al. (2013). Additionally, soil texture was determined by the micro-pipette method (Burt et al., 1993). In-field soil assessment of 25 of the 29 trials was conducted in 2016 using the LandPKS app where soil texture by depth was recorded using soil-texture-by-feel and rock fragment categories noted at 0–10 cm, 10–20 cm, 20–50 cm, 50–70 cm, and 70–100 cm depths per LandPKS protocol. Soil restrictive layers (compaction and lateritic material) were also recorded. Output provided by the app included local climate and estimated plant available water holding capacity (AWC) up to 1 m based on soil texture (Saxton and Rawls, 2006).

Table 1

Description of extension planning areas (EPAs) where trials were conducted including climate, soil, and local infrastructure characteristics.

EPA	Linthipe	Golomoti	Kandeu	Nsipe
Trial sites (n)	8	7	7	7
Latitude/Longitude	14.21°S, 34.10°E	14.44°S, 34.60°E	14.63°S, 34.60°E	14.93°S, 34.74°E
Elevation (m)	1230	553	907	892
Temp Range (°C)[a]	18–32	21–35	19–32	19–32
Rainfall (mm)[b]	975 (775–1417)	797 (638–1082)	922 (732–1265)	951 (733–1304)
Soil classification[c]	Ferric LuvisolsChromic Luvisols	Chromic CambisolsGleysols	Chromic CambisolsFerralsols/Gleysols	FerralsolsOrthic Ferralsols
Distance from small market (km)[d]	5	1	2	9
Distance from large market town (km)[d]	40	40	35	20

[a] Average minimum and maximum temperature throughout the growing season (November–April) from 2009 to 2019, data extracted from MODIS Terra Land Surface Temperature (Wan et al., 2015).

[b] Rainfall reported as 10-year average and range (2009–2019), data extracted from CHIRPS (Funk et al., 2015).

[c] First and second most common soil class based on FAO's Harmonized World Soil Database and improved prediction by LandPKS SoilID.

[d] Survey data reported in Mungai et al. (2016).

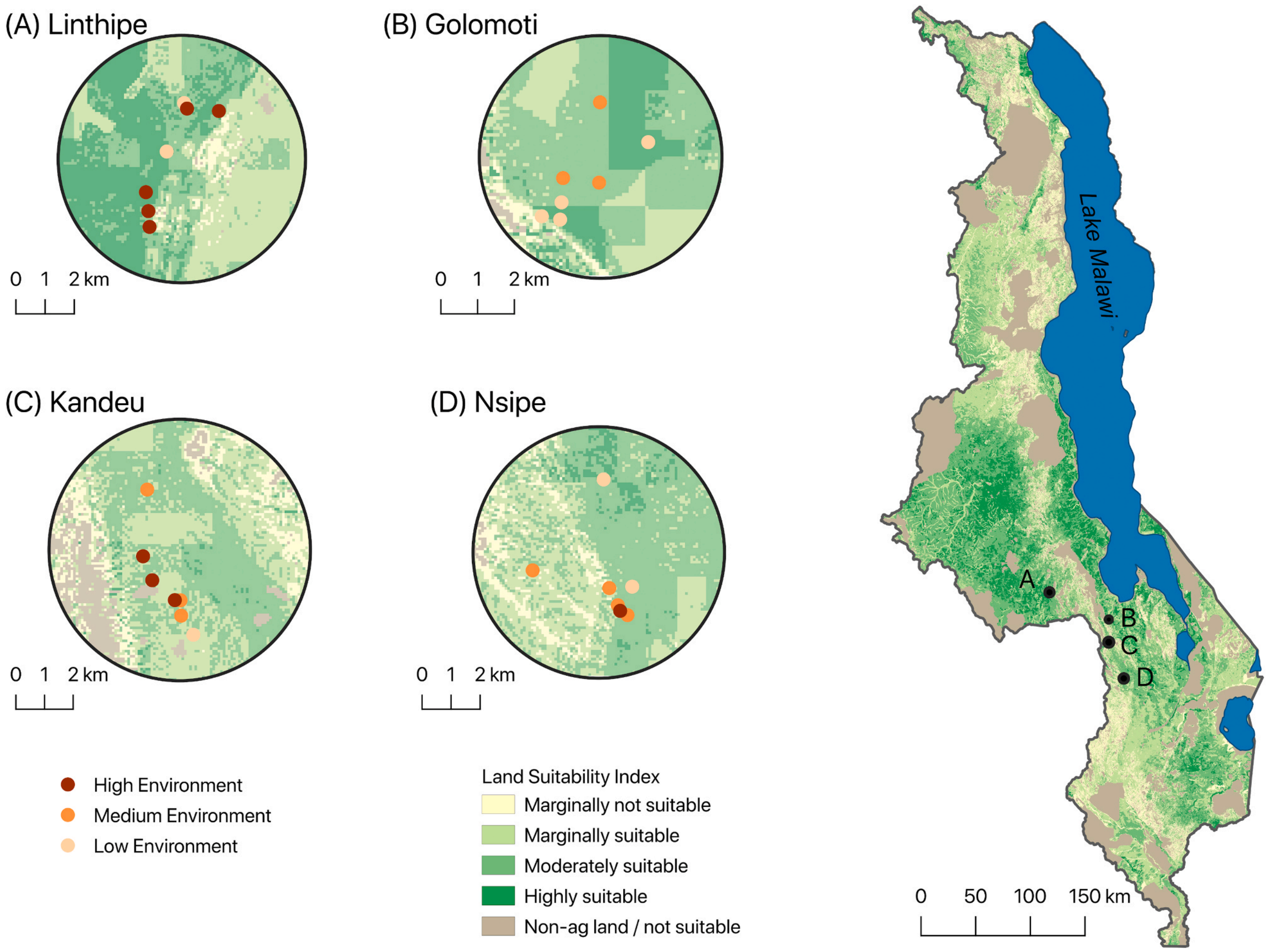

Fig. 1. Land suitability classification is based on Li et al. (2017) and shown here for four EPAs in Central Malawi (Linthipe, Golomoti, Kandeu and Nsipe). The twenty-nine farm experimental sites are presented by EPA, and identified as high, medium, and low yield environments based on long-term mean maize yield (across all plots per site).

Table 2
Descriptions of the cropping systems assessed in this study. The systems received the fertilizer dose shown only when maize was present (every year for continuous and intercrop systems Mz0, MzNP and MzPp, and every other year for rotations DLR, GnRot and PpRot).

System description	Abbreviation	Fertilizer kg ha^{-1} (N and P_2O_5-P)	Plant population (plants m^{-2})		
			Maize	Groundnut	Pigeonpea
Continuous sole maize, unfertilized	Mz0	0N 0P	5.3	NA	NA
Continuous sole maize, full-fertilized	MzNP	69N 21P	5.3	NA	NA
Pigeonpea intercropped with groundnut year one, Maize year two	Doubled up Legume Rotation (DLR)	34.5N 10.5P	5.3	13.3	4.4
Groundnut year one, Maize year two	GnRot	34.5N 10.5P	5.3	13.3	NA
Pigeonpea year one, Maize year two	PpRot	34.5N 10.5P	5.3	NA	4.4
Continuous Maize- Pigeonpea intercrop	MzPp	34.5N 10.5P	4.4	NA	4.4

Crop grain yield was harvested each year in experimental plots, as follows. Crop harvest was conducted at plant maturity (mid-April for groundnut and maize, late July for pigeonpea) for a net plot of three middle rows spaced at 0.75 m, each 9 m in length ($3 * 0.75 * 9 = 20.25$ m^2). Biomass of stems and leaves were measured in the field and a subsample removed from the field to be oven-dried, and subsequently, dry weight was determined. In addition, in the field, legume pods and maize cobs were removed and threshed. Grain was air-dried for four to five weeks until grain moisture had dropped to at least 150 g kg^{-1}, and then weighed. Grain moisture was determined using a DICKEY-john moisture meter (Churchill Industries, Minneapolis, MN) and weights were adjusted per agronomic protocols to 130 and 125 g kg^{-1} moisture content for legumes and maize, respectively (Chimonyo et al., 2019). For grain and biomass data, two-year data were summed for all systems to facilitate comparison of rotational systems to intercrop and sole crop. This included two consecutive years for intercrop and sole crops, and the legume phase followed by the maize phase for rotation systems.

2.4. *Environment characterization for analysis*

The four EPAs with on-farm experiments were characterized based on a land suitability index for Malawi (Fig. 1) (Li et al., 2017). This country-wide suitability index was developed for agricultural land with indicator scores calculated from soil properties (texture, SOC, CEC, pH, depth, drainage), typography (slope steepness, length), and rainfall intensity (rainfall-runoff erosivity). The indicators included soil erosion risk (Revised Universal Soil Loss Equation (RUSLE)) and soil characteristics, which were then averaged and classified to create four land suitability classes (Highly suitable, moderately suitable, marginally suitable, marginally not suitable).

To assess experimental site-specific yield potential, sites were classified as high, medium, or low based on average maize yield (across all maize cropping systems) over seven years. This is an approach widely used in plant breeding to calculate an environmental index and assess genetic performance by environment (Setimela et al., 2017; Kante et al., 2017). For on-farm experimentation, this approach accounts for farm management quality, soils, and climatic differences (Smith et al., 2016). In this study, we contextualized cropping system performance by characterizing environments as being low to high potential, at the scale of individual farms rather than using the coarse scale of administrative boundaries. Based on mean maize yield, each farm site was categorized as a low yielding environment (500–2000 kg ha^{-1}), medium yielding environment (2001–3050 kg ha^{-1}) or high yielding environment (3051–4700 kg ha^{-1}). These categories were derived based on a cluster analysis of farmer's mean maize yield across all systems and years at a given site (Brentari et al., 2016; Dancelli et al., 2013).

2.5. Protein contribution analysis

Protein contributions of grain yield from each SI system is evaluated. based on Van den Brand (2011) and Salunkhe et al. (1986). The authors used a nutritional value of protein at 9% for maize, 26% for groundnut and 24% for pigeonpea. The percentage protein content of each crop was multiplied by the grain weight to obtain the protein contribution for each system. This was then.

2.6. Statistical analysis

A fixed effect two- way analysis of variance (ANOVA) model was conducted on grain yield, biomass, protein contribution, and economic returns on environment and cropping system using R (ver. 3.6.2, R Development Core Team) and Stata software (ver. 16, StataCorp, College Station, TZ, USA). A two-way fixed effects ANOVA model is given as:

$$Y_{ij} = \mu + \alpha_i + \gamma_j + \alpha\gamma_{ij} + \varepsilon_{ij} \tag{1}$$

$$\alpha\gamma_{ij} \sim N\left(0, \delta^2\right), \varepsilon_{ij} \sim N\left(0, \delta^2\right) \quad \text{for every } i = 1 \ldots 3 \text{ and } j = 1 \ldots 5$$

where Y_{ij} is the outcome for every observed value of grain yield, biomass, protein, and economic returns; µ is the overall mean; α_i is the effect of environment at associated with level *i*; γ_j is the effect associated with level *j* of cropping system effect; $\alpha\gamma_{ij}$ is the interaction effect of environment and cropping system of level *ij*; and ε_{ijk} is a random deviation with mean zero.

Trials were established sequentially as the project expanded to new locations, and some trials did not persist due to factors such as road construction or farmer life events. This led to a range of duration over the study sites; however, this was not included in the ANOVA model as diagnostic models were run and showed no effect of longevity of establishment when comparing two-year, four-year, and six-year studies.

A planned mean comparison test was conducted for rotation legume systems (PpMz, GnRot, and DLR), intercropping (MzPp), and continuous maize unfertilized. The mean test was conducted using linear contrast of means for all legumes systems to maize unfertilized. This was then followed by a within legume systems comparison of rotations (MzPp, GnRot, and DLR) versus maize-pigeonpea intercrop (MzPp). In addition to a sole maize control system, a maize-pigeonpea intercrop is another form of control and so included in a contrast. The analysis of protein and grain contribution by each system was conducted for the high, medium, and low environments. First, a means comparison was conducted for all legume systems vs. continuous unfertilized maize. Second, a within legume systems means comparison contrasted DLR vs other legume systems (GnRot, MzPp, PpRot). Transformation using the natural log was used for protein data to achieve normally distributed data (Knapp and van der Heijden, 2018).

2.7. Stability analysis

An additive main effects and multiplicative interaction (AMMI) model was performed to describe the factor interaction of grain and protein yield for SI systems across environments. AMMI was calculated to assess stability of systems across environments as follows:

$$Y_{ij} = \mu + \partial_i + \beta_j + \sum_n \gamma_n \delta_{jn} + \rho_{ij}$$

where Y_{ij} is the yield of genotype *i* in environment *j*; μ is the grand means; and ϑ_i is the is the genotype deviation from the grand mean; β_j is the environment deviation; γ_n is the singular value for interaction principal component (PC) *n* and correspondingly γ_n^2 is its eigenvalue; δ_{in} is the eigenvector value for genotype *i* and component *n*; φ_{jn} is the eigenvector value for environment *j* and component *n*, and ρ_{ij} is the residual (Annicchiarico, 1997; Gauch Jr, 1992; Yan et al., 2007).

For the stability analysis two interaction principal components (PC) were established for environment and cropping system interaction. Cropping systems with large PC scores (i.e., where most of the variance in the dataset lies) were considered to have large interaction and were hence highly variable (Chimonyo et al., 2019; Gubatov et al., 2017; Asaro et al., 2016). A biplot was constructed by plotting the first principal component (PC1) scores of the cropping systems and environments against their respective scores for the second principal component (PC2). The relationship between the two scores was defined as low interaction or variation with scores close to zero. Stability is likely to be correlated with different environmental factors and cannot fully be based on the cropping system only.

To understand grain and protein variability over space the coefficient of variation (CV) was calculated for each cropping system for comparison relative to the mean of each system. The CV gives the relative measure of variation unlike other methods that provide an absolute comparison (Anderson et al., 2020). The cropping systems were categorized into three groups, i.e., rotation (GnRot, PpRot and DLR), intercrop (MzPp) and sole (Mz0). The mean and standard deviation for each cropping system was calculated, and then their ratio (CV). The CV results were then tested for statistical difference using a two-way ANOVA, and thereafter a mean comparison test was conducted for systems as described above for yield response.

2.8. Economic analysis

The assessment of profits (economic returns) was evaluated for all sites where the SI systems included full fertilized as well as unfertilized sole maize. This was a subset of 14 farm sites. The analysis took into account both fixed and variable costs that vary across cropping systems, including input costs such as the cost of seeds (pigeonpea, groundnut and maize), fertilizer (NP and urea) and labor costs (man day per ha multiplied by the price of labor per day) (Komarek et al., 2018).

Based on a study in neighboring Mozambique, Rusinamhodzi et al. (2012) estimated the quantity of labor required annually for production of sole maize at 17.6-man days per hectare, for sole pigeonpea at 18.2-man days per hectare, and for sole groundnut, 22.3-man days per hectare. Intercropping maize and pigeonpea was estimated to increase weeding time by 36% on average. Labor costs for Malawi smallholders were based on our own survey, and on a previous study by Ngwira et al. (2012), to derive high and low daily price scenarios of 2.61 US$ and 1.9 US$, respectively. The labor costs and quantity were also checked against the labor costs observed at our trial sites (Snapp et al., 2018). The cost of fertilizer was based on the prices charged by local fertilizer suppliers. The estimated total cost of production for each SI system was established by summing all fixed and variable costs.

Total revenue of each system was calculated based on yield produced and average crop prices. The associated prices for maize, groundnut and pigeonpea were based on prices received by farmers as reported in the baseline survey, and market prices collected at the trial locations (Snapp et al., 2018). The average prices were kept constant using 2016 as the base year. The 2017 export ban in Malawi affected legume prices. To consider the effect of high vs low relative prices for legume grain, a sensitivity analysis employed low and high legume price scenarios, relative to the maize price. The first scenario: maize price (0.30 US$ kg^{-1}), pigeonpea (0.30 US$ kg^{-1}) and groundnut (0.45 US$ kg^{-1}). The second scenario simulated a likely price when supply is low with an assured export market, whereby the legume prices were increased by 50% of the former price with pigeonpea price at 0.45 US$ kg^{-1} and groundnut 0.67 US$ kg^{-1}. The estimated costs and revenues were then used to calculate the gross margins and profitability of each system, for the two scenarios. The formulas used were as follows:

Fixed costs (cost of inputs) = Cost of fertilizer + Cost of seed.

Variable costs (labor cost) = Labor price ($USD) × Labor quantity (people days per hectare).

Total Cost of production: fixed costs + variable costs.

Total revenue = Yield in kg/ha × Price/kg.

Gross margins = Total Revenue – Total cost of production.

3. Results

3.1. Environment and site context

The land suitability of the sites in this study are shown in Fig. 1, based on an index developed by Li et al. (2017). Overall, Linthipe is a highly mesic site, with land that is largely classified as high suitability for agriculture, with well distributed rainfall across most study years, and a moderate temperature range that favors field crop growth (Table 1). Golomoti is much less suitable for crop production, with much of the land classified as marginal, a hotter temperature range and variable rainfall. The other two EPAs are intermediate in land suitability.

In addition to land heterogeneity, we expected there to be agricultural management differences by site, given the variability of conditions within EPAs (Fig. 1). In general, Linthipe had the greatest proportion of high environments (5 out of 7 sites) and Golomoti the lowest (0 sites), with Kandeu and Nsipe characterized as a mix of high and medium environments. While characterizing the Golomoti sites by environment shows this area to be generally low yielding, there are areas of high land suitability as identified in the Li et al. (2017) index. Linthipe had both a large proportion of high environment sites and a large proportion of highly suitable land conditions. Kandeu and Nsipe were both characterized as mixed environment and land suitability areas, with a greater proportion of moderately suitable land as well as a greater range of high to low environment sites compared to Linthipe and Golomoti.

Characterization of the soil properties was conducted for a subset of farm sites (Table 3). Sites had generally similar soil properties in respect to SOC, soil texture, available water holding capacity (AWC), and presence of restrictive layers. Sites were almost all low in SOC (means of 0.7–1.38%, across all environments) and very low in N (0.05–0.08%). An evaluation of site labile carbon pools was conducted by carrying out laboratory analysis of POXC and Cmin. These indicators of soil C labile pools followed similar trends to that observed for total SOC. Average soil texture also did not differ across environments with each environment category including soils ranging from coarse to fine texture.

Table 3
Average soil characteristics of low, medium, and high environment sites.

Environments	Low	Medium	High
Total C (%)[a]	1.04 (0.53)	0.7 (0.25)	1.38 (0.73)
POXC (mg kg^{-1})[a]	445 (291)	395 (333)	629 (285)
Cmin (mg kg^{-1})[a]	18.6 (6.3)	17.4 (5.5)	24.2 (9.2)
Total N (%)[a]	0.07 (0.03)	0.05 (0.01)	0.08 (0.03)
% Sand[a]	58 (21)	64 (14)	58 (16)
% Clay[a]	21 (14)	22 (11)	21 (12)
AWC to 1 m (cm)[b]	11.2 (2.8)	12.0 (2.8)	12.7 (2.0)
Restrictive layers[b]			
Compaction	25%	30%	50%
Laterite	25%	20%	25%

[a] Determined by laboratory analysis.

[b] Determined through LandPKS application output and supplemental observations in sampling site soil profiles to 1 m

3.2. Cropping systems and soil properties

In evaluating cropping system effects on soil properties, a marked interaction between SOC and soil texture was observed; this had an overriding effect. No SOC differences by cropping system treatment were detected. Additionally, soil measures such as POXC and Cmin did not vary by cropping system, and followed closely SOC levels to texture. Overall, coarse-textured sites were found to be low in SOC. Fine-textured sites varied in terms of SOC, although generally these sites were high compared to coarse-textured sites. Thus, sites with less than 40% sand had 1% C or higher (Fig. 2).

Interestingly, comparing SOC across soil texture by environment shows a trend amongst groups in that SOC was often high at environments assessed to have high maize yield potential (Fig. 2A). This pattern of SOC and maize yield potential category (environment) was only discernible on fine-textured sites (left side of Fig. 2A). Differentiation of site by trial age revealed that older trial sites (>5 years) were predominately on coarse sandy soils, whereas newer sites (<2 years) consisted of a range of clay and sand sites (Fig. 2B). There may have been inadvertent consequences of this limited range of soil texture representation in our long-term trial sites. The evidence presented here is consistent with a reduced ability to detect cropping system effects on SOC in sandy sites. Fig. 3A shows that at fine textured sites (<50% sand), SOC ranged from 1% to 3%, whereas at coarse sites (>73% sand) SOC varied from 0.5% to a little over 1%.

3.3. Grain yield and biomass

Cropping system and environment both show a strong influence on grain yield and biomass (Table 4). An interaction effect between cropping system and environment was observed for grain yield ($p < 0.004$) and for biomass ($p = 0.014$). The mean values for grain yield are shown in Fig. 4, with a range of 1.8–7.8 t ha^{-1} across all environments and systems. The mean biomass production varied between 4.9 and 15.2 t ha^{-1}, with a systems response pattern that followed closely that of grain yield; values are provided as supplementary results (Fig. A1).

A marked effect of legume systems is observed for grain yield and biomass, as all outperformed the maize control (unfertilized continuous sole maize). This control system is practiced on 23% of farmer fields in Central Malawi (Mungai et al., 2016). We note that the legume systems are moderately fertilized, at 17.25 kg N ha^{-1} for rotations (DLR, GnRot, PpRot) and 34.5 kg N ha^{-1} for the intercrop (MzPp). Across all environments, unfertilized sole maize yield was low (3.2 T ha^{-1} 2 yr^{-1}), and substantially lower than all legume systems. Sole maize produced a high grain yield of 5.2 ha^{-1} over two years in high yield, mesic environments, with high variability from site to site. This yield was much closer to legume diversified systems than in marginal environments (Fig. 4).

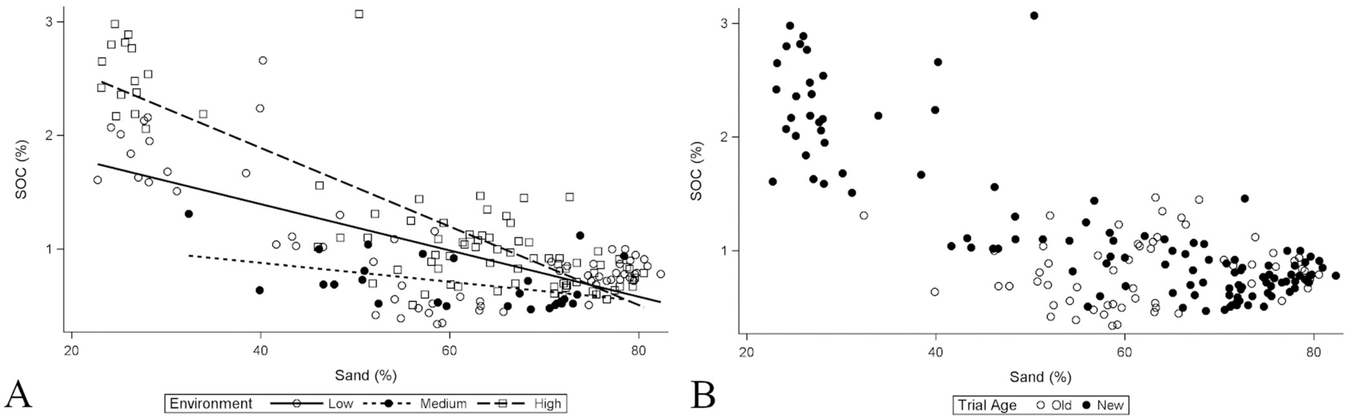

Fig. 2. SOC (%) across soil texture types by environment (A) and by trial age (B). Old trial sites were in their 5th or 6th trial year and new sites were in their 1st or 2nd trial year.

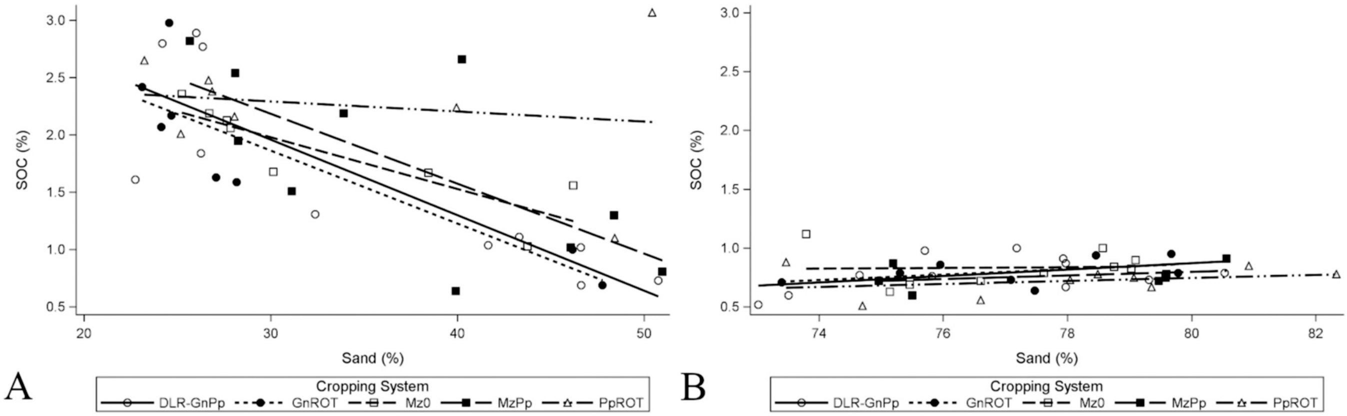

Fig. 3. SOC (%) by cropping system across soil texture types, where panel A shows sites in the lower 25% percentile for sand and panel B shows sites in the upper 75% percentile for sand.

Table 4
Analysis of variance and planned contrasts for grain yield, biomass, and protein over two years by cropping system. SI systems shown are unfertilized maize (Mz0); doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnuts with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) and maize and pigeonpea intercrop (MzPp).

	Grain yield		**Biomass**		**Protein**	
	Contrast	**Pr >F**	**Contrast**	**Pr >F**	**Contrast**	**Pr >F**
DLR vs Mz0	1.93	0.000***	2.97	0.001***	1.11	0.001***
GnRot vs Mz0	1.67	0.000***	2.32	0.005***	1.12	0.001***
PpRot vs Mz0	2.43	0.000***	2.41	0.069*	0.84	0.001***
MzPp vs Mz0	2.28	0.000***	3.91	0.001***	0.73	0.001***
DLR vs MzPp	–0.35	0.635	–0.94	0.485	0.37	0.001***
GnRot vs MzPp	–0.61	0.238	–1.59	0.127	0.39	0.001***
PpRot vs MzPp	0.14	0.997	–1.50	0.481	0.11	0.741
ANOVA						
	F value	**Pr >F**	**F value**	**Pr >F**	**F value**	**Pr >F**
Cropping System (CS)	24.29	0.000***	12.40	0.000***	106.65	0.000***
Environment (Env)	104.40	0.000***	53.95	0.000***	79.28	0.000***
CS x Env	2.83	0.004***	2.42	0.014**	6.73	0.000***

Significance levels: *** at 1%, ** at 5% and * at 10%.

Overall, performance of grain yield and biomass in legume systems were all better than continuous sole maize and were not differentiated from each other. We compared the legume rotation systems (DLR, GnRot, PpRot) to the maize pigeonpea intercrop (MzPp), as another form of a control system. This intercrop is practiced widely by farmers in Southern Malawi, at various levels of fertilization, but it is rarely observed in Central Malawi. The grain yield and biomass of MzPp was not detectably different from the other legume diversified systems.

Two measures of system variability were conducted for grain yield, one was an ANOVA of coefficient of variation (CV), and the other was a stability analysis. The results of the CV are presented in Table A.1 and Fig. 5. ANOVA results for CV showed a high interaction effect of the cropping systems and environment at a 1% level ($p = 0.000$). In the mean comparison test, all systems' CV varied. The three rotation systems were compared in a planned contrast to the intercrop and sole maize continuous system. Very high variability is shown for grain produced by

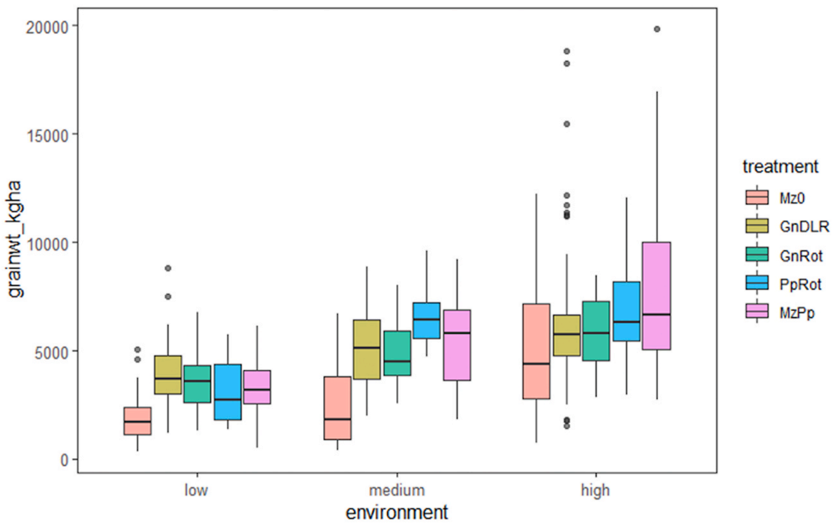

Fig. 4. Grain yield (Kg ha^{-1} 2 yr^{-1}) of systems on a two-year basis by environments (low, medium, and high). The midline denotes the system's median; the colored box corresponds to 25% above and 25% below the median and circles show outlier values. The cropping systems shown are maize unfertilized (Mz0), doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnut with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) and maize and pigeonpea intercrop (MzPp) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

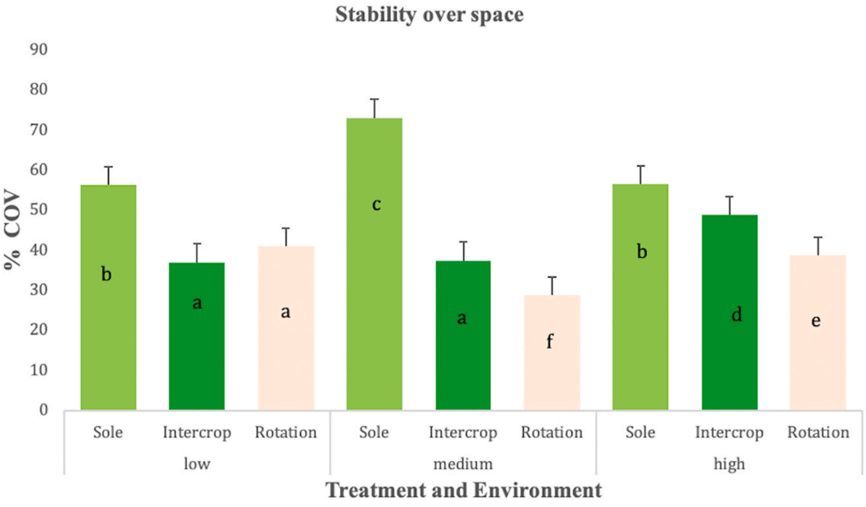

Fig. 5. Grain yield planned contrasts of the Coefficient of Variation (CV) results for the cropping systems across different environments. Bars with the same letters are not significantly different from each other at a 5% significance level. The five cropping systems were recategorized into three cropping systems. Unfertilized maize (Mz0) as sole system; doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnuts with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) as rotational systems; and maize and pigeonpea intercrop (MzPp) as intercrop system.

sole unfertilized maize systems, with a CV of 56–73% (Fig. 5). Among SI legume systems, rotations were consistently associated with the lowest CV, this is shown in both medium and high environments, at 29–41% whereas the intercrop demonstrated intermediate variability (Fig. 5).

The AMMI analysis explained 62% and 38% of the systems variability for the first and second principal components (PC1 and PC2), respectively, with clear distinctions by environment (Fig. 6). The two PCs in the AMMI model were statistically significant (P values PC1 = 0.0074 and PC2 = 0.0251), the high yielding environment was the most stable one for all systems. Pigeonpea-maize rotation and maize unfertilized systems were associated with higher fluctuations in grain yield across environments and high PC scores (Fig. 6). The maize

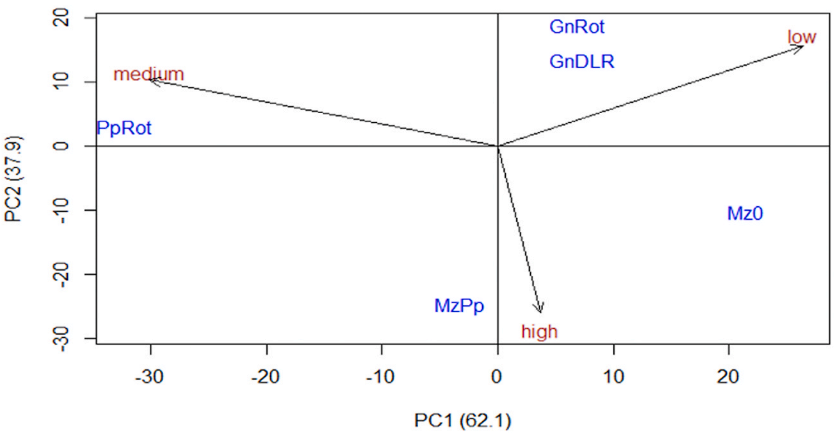

Fig. 6. Additive main effect and multiplicative interaction (AMMI) biplot principal component (PC) 1 and 2 scores for grain yield and SI systems, maize unfertilized (Mz0), doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnuts with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) and maize and pigeonpea intercrop (MzPp). The three yielding environments are low, medium, and high. Horizontal and vertical lines show the interaction scores deviation from zero.

unfertilized system was relatively stable in a high yielding environment and performed poorly in a low and medium yielding environment. Maize-pigeonpea intercrop system was stable in a medium and high environment with low PC score close to the origin. The two groundnut systems, DLR and GnRot systems, were stable in a low yielding environment.

3.4. Protein

At all sites, and for all cropping systems, continuous maize unfertilized (Mz0) systems produced the lowest protein (300 kg ha^{-1} 2 yr^{-1}) (Table 4). Differences varied across and within environments, with DLR and groundnut rotation producing the most amount of protein in the low potential environment (Fig. 7). Systems with groundnut (DLR and GnRot) produced more than two-fold the level of protein of Mz0, at 758 kg ha^{-1} 2 yr^{-1} and 682 kg ha^{-1} 2 yr^{-1}, respectively. Pigeonpea intercrop and rotation (MzPp and PpRot) systems produced intermediate amounts of protein at 527 kg ha^{-1} 2 yr^{-1} and 547 kg ha^{-1} 2 yr^{-1}, respectively. Overall, groundnut appeared to be the main basis for protein production (Table 4).

Stability of protein performance was also assessed by AMMI model. The first PC1 contributed 72.5% (p-value = 0.000) and the second PC2 contributed 27.5% (p-value 0.0067) to the variability associated with environments and cropping systems (Fig. 8). Unfertilized maize (Mz0) was a highly variable system with a high PC score and was only stable in a high yield environment. Protein contribution under GnRot and DLR showed the least variation, most notably for DLR in the low yield environment. Thus, protein contribution from groundnut systems was not only high, but remained stable in marginal conditions. Systems with pigeonpea (PpRot and MzPp) produced protein that was generally stable across medium and high yield environments (Fig. 8).

3.5. Economic returns

For the economic analysis we used a subset of the sites (14), those that included a continuous, sole maize system that was fertilized at the full, government recommended rate of 69 kg N, 35 kg Phosphate-P per ha. The FISP subsidy in Malawi enhances access to fertilizers among smallholders, and we wanted to represent this option. Based on average market prices the revenue and gross margin results for each cropping system are presented in Table 5. To evaluate the effect of variable crop prices which occur over seasons and locations, we conducted a scenario analysis with low grain legume prices relative to the maize grain price. There was limited differentiation in system profitability under this low legume price scenario; see supplemental results (Table A.3).

To calculate returns we first considered the production costs, which are presented as the combined input and labor costs over two years (to facilitate comparisons of two-year rotations to other cropping systems). The Mz0 system had the lowest production cost ($129.37) whereas the fully recommended fertilized rate applied to sole maize (MzNP) had the highest cost ($449.32). Intermediate costs were associated primarily with groundnut seed and fertilizer inputs, as observed for DLR, GnRot and Maize pigeonpea intercrop at $366.5, $349.2, and $320.7, respectively (Table 5).

The gross margins for unfertilized maize (Mz0) were much lower than all the other systems (Table 5), at $633 compared to the highest at $2119 $ ha^{-1} 2 yr^{-1}. The fertilized maize system had the highest gross margin, and intermediate returns were observed from the legume systems which were not different from each other, following this pattern: MzNP = DLR = GnRot = MzPp > PpRot > Mz0 (Table A.3).

4. Discussion

4.1. Site soil properties and effect on cropping system

This study includes a wide range of on-farm sites where soil texture, SOC and the interaction of the two stand out as key soil characteristics for contextualizing site performance. The results were consistent with crop performance in high yield environments as being supported by high SOC, at least for fine-textured soils. This trend was not observed in coarse soils, which points to complex interactions that drive crop performance. While increasing SOC pools is often proposed as a key aspect to sustainably improving yields, our results show the limitations to increasing SOC for many sites, depending on underlying particle size distribution properties (Lal, 2006). Consideration of soil properties, and texture in particular, is an often-overlooked context for crop management recommendations, as shown by a number of on-farm studies in East Africa (Roobroeck et al., 2021; Tittonell et al., 2008). The implication of these findings is that crop management that relies on organic sources of fertility may require close attention to soil texture.

Monitoring SOC allows for assessing the long-term sustainability of cropping systems. We found that SOC did not differ by system, which may have been related to the challenges described above, associated with SOC accrual in coarse-textured soils. Initially, the trials sites were chosen to represent a wide range of soil texture and environmental potential, however a number of the fine-textured sites were lost over time due to unavoidable circumstances such as road construction and farm ownership changes. While legume diversification in cereal-based

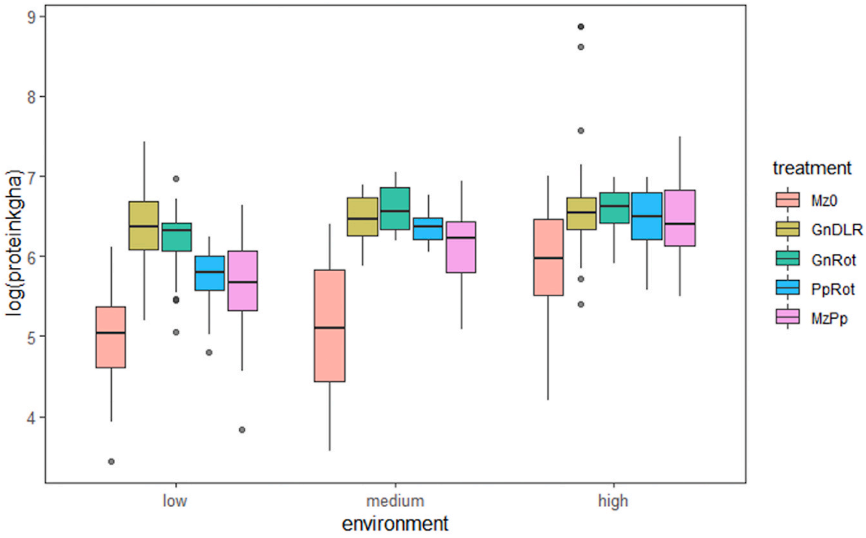

Fig. 7. Protein contribution of systems on a two-year basis by environments (low, medium, and high). The midline denotes the system’s median; the colored box corresponds to 25% above and 25% below the median and circles show outlier values. The cropping systems are sorted form maize unfertilized (Mz0), doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnuts with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) and maize and pigeonpea intercrop (MzPp) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

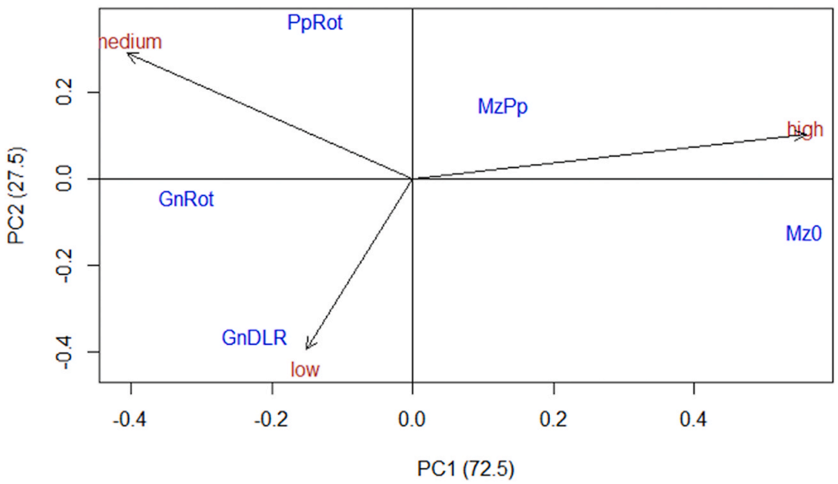

Fig. 8. Additive main effect and multiplicative interaction (AMMI) biplot principal component (PC) 1 and 2 scores for protein contribution of five SI systems on a two-year basis; maize unfertilized (Mz0), doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnuts with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) and maize and pigeonpea intercrop (MzPp). The three yielding environments are low, medium, and high. Horizontal and vertical lines show the interaction scores deviation from zero.

Table 5
Economic analysis of six cropping systems in central Malawi at high Legume prices. Cropping systems shown are maize unfertilized (Mz0), maize fertilized (MzNP) doubled up legume pigeonpea intercropped with groundnut and rotated with maize (DLR), groundnuts with maize rotation (GnRot), pigeonpea with maize rotation (PpRot) and maize and pigeonpea intercrop (MzPp). The cropping systems are assessed over two years. The table includes the gross margins comparisons for the systems.

HIGH	Units	Mz0	MzNP	DLR	GnRot	PpRot	MzPp
Fertilizer (basal – NP)	$\$$ 50 kg of grain^{-1}	0	80	40	40	40	40
Fertilizer (top – Urea)	$\$$ 50 kg of grain^{-1}	0	80	40	40	40	40
Maize seed	$\$\ \mathrm{ha}^{-1}$	18.75	18.75	18.75	18.75	18.75	15.57
Pigeonpea seed	$\$\ \mathrm{ha}^{-1}$	0	0	6.6	0	6.6	6.6
Groundnut seed	$\$\ \mathrm{ha}^{-1}$	0	0	156.96	156.96	0	0
year 1	$\$\ \mathrm{ha}^{-1}$	18.75	178.75	163.56	156.96	6.6	102.17
year 2	$\$\ \mathrm{ha}^{-1}$	18.75	178.75	98.75	98.75	98.75	102.17
Total input costs	$\$\ \mathrm{ha}^{-1}\ 2\ \mathrm{yr}^{-1}$	37.5	357.5	262.31	255.71	105.35	204.33
Labor costs	$\$\ \mathrm{ha}^{-1}\ 2\ \mathrm{yr}^{-1}$	91.87	91.872	104.14	93.44	93.44	116.41
Total costs	$\$\ \mathrm{ha}^{-1}\ 2\ \mathrm{yr}^{-1}$	129.4	449.3	366.5	349.2	198.8	320.7
Average Revenue	$\$\ \mathrm{ha}^{-1}\ 2\ \mathrm{yr}^{-1}$	762.9	2567.9	2002.8	2342.9	1663.6	2051.7
Average Gross margin	$\$\ \mathrm{ha}^{-1}\ 2\ \mathrm{yr}^{-1}$	633.5	2118.6	1636.3	1993.7	1514.5	1731.0

Gross Margin Comparison

	Contrast	P-value
MzPp-MzNP	–387.6	0.8481
PpRot-MzNP	–604.1	0.4889
DLR-MzNP	–482.2	0.7016
GnRot-MzNP	–124.8	0.9988
Mz0-MzNP	–1485	0.0051
DLR-Mz0	1002.8	0.0782
GnRot-Mz0	1360.2	0.0105
PpRot-Mz0	880.9	0.1474
MzPp-Mz0	1097.4	0.0466
PpRot-MzPp	–216.5	0.985
DLR-MzPp	–94.7	0.9997
GnRot-MzPp	–262.8	0.9656
GnRot-DLR	357.4	0.8855
PpRot-DLR	–121.8	0.999
PpRot-GnRot	–479.3	0.7067

cropping systems has been shown to increase SOC, these effects have been frequently observed with tree legumes and at long-term trial sites (Beedy et al., 2010). One of the two legume species studied here, pigeonpea, has been shown to be associated with SOC accrual at research station sites (Vieira et al., 2007), although this has not been verified in on-farm studies where soil variability is high (Snapp et al., 2010). This highlights the challenges to document and promote SOC improvement under smallholder farming conditions (Cong et al., 2015; Hazra et al., 2019).

The remaining trial sites with fine-textured soils were found to have the greatest range of SOC and thus the greatest potential in identifying cropping system effects. Sites with fine-textured soil were younger trials (2 growing seasons) and overall, there was a lack of fine-textured longer-term sites (>5 growing seasons) to support detection of SOC changes. Few on-farm studies have been conducted over the ten or more years that support observations of changes in soil C status, and our multi-site, multi-year study highlights these challenges are acute for on-farm research (Smith, 2004).

4.2. *Yield of grain, biomass, and protein*

SI systems with legume diversification and modest fertilization consistently out-performed unfertilized maize by producing substantially more grain, biomass, and protein. For Malawi smallholders, market access is often limited and farm size small, thus quantity of grain matters every year, not just in a response to a rotation year (Smith et al., 2017). Quality of grain produced by crop species was also considered, in the protein metric and the economic returns. Sole unfertilized maize control system produced 3.2 T ha^{-1} 2 yr^{-1} and legume-diversified systems produced an additional 1.8–2.5 T ha^{-1} 2 yr^{-1} of grain yield compared to the unfertilized system. This is in the range of earlier reports from Central Malawi, although higher than most (Chimonyo et al., 2019; Smith et al., 2016). Biomass productivity associated with SI systems was also high, decidedly higher than the gains associated with grain. This is suggestive that early plant growth was favored by this SI combination of fertilizer (17.5–35 kg of N ha^{-1}) plus legume residues.

The highest differentiation for performance of the SI systems is shown when protein produced is considered. This was expected, as leguminous crops produce high quality grain, with protein concentration for pigeonpea and groundnut in the range of 20–26%, whereas maize is about 9–10% (Salunkhe et al., 1986). However, the extent of protein production on smallholder farms is not well known, and our finding that protein can be as high as 300–758 kg ha^{-1} 2 $yr^{-1}$is consistent with promotion of SI systems as nutritional interventions. This supports findings from northern Malawi where an agroecology project, supported by a local hospital, has shown child nutritional gains through the combination of participatory education and promotion of legume crops (Bezner Kerr et al., 2011).

Next, we considered the two types of legume diversity tested, that of intercrop and rotational systems. A maize-pigeonpea intercrop system has been shown previously to be a superior legume diversified system, producing enhanced maize yield over sole maize systems in almost all cases, from nil to over 100% (Myaka et al., 2006; Bezner Kerr et al., 2007; Snapp et al., 2002). The infertile, coarse soils typical of smallholder farms in Zimbabwe show the versatility of a maize-pigeonpea intercrop, which produced modest but persistent yield benefits in that environment as well (Waddington et al., 2007b). Our study showed that rotational systems can perform as well, and in the case of groundnut diversified systems, rotations were often better than a maize-pigeonpea intercrop (Table 4).

The modest fertilizer doses tested in association with legume-diversified systems are an example of how farmers can most effectively use the one or two bags of fertilizers accessed through government subsidies (Wang et al., 2019). The SI systems assessed here varied in fertilizer requirements, with the maize-pigeonpea intercrop receiving 34.5 kg N ha^{-1} annually, twice as much as the requirements for a rotational system which have a maize phase every other year. Fertilizer use is very expensive in the Malawi context and economic returns for SI systems can vary markedly, depending in large part on the relative prices of maize, legume, and fertilizer (Franke et al., 2014; Snapp et al., 2018).

Legume-cereal rotational studies often report cereal yield response to rotation. For example, in a 12-year maize-groundnut rotation study in Zimbabwe a 10–15% maize yield gain was shown compared to continuous maize (Waddington et al., 2007a). Yet, this translates into poor productivity in terms of grain produced overall, as groundnut yields were 0.15–0.37 T ha^{-1}, a modest twenty to fifty percent of maize yields at this sandy site. Indeed, if a criterion of grain produced on a two-year basis is used, then many rotational systems of legume-cereal produce less than cereal monocultures. There is considerable variability in cereal response to legume crops in rotational systems, as shown by a recent review of studies in Africa, which reported cereal yield gains from 17% to 100% relative to production of cereal following cereal (Franke et al., 2018). At the high end of these studies, a multi-site study in Kenya, found that maize grain produced in a maize-groundnut rotation vs continuous maize was ~70–80% higher (Ojiem et al., 2014).

Our findings for rotational systems were higher than most previously reported, with two-fold and higher gains in the response year, and higher grain yield over all compared to continuous, unfertilized, sole maize. This high performance was largely due to high groundnut grain yields. This was achieved at dozens of on-farm sites. In contrast, pigeonpea yields were 0 kg ha^{-1} at many sites, and as high as 1529 kg ha^{-1} at one site, with an overall average of 994 kg ha^{-1} (SD 965 kg ha^{-1}). This low productivity has been previously reported in a multi-site ESA pigeonpea study (Myaka et al., 2006). Generally, legumes have a modest yield potential relative to cereal crops based on the photosynthetically expensive processes that legumes support, e.g., biological nitrogen fixation and production of protein-rich seeds (Janila et al., 2013). Thus, the high groundnut yields produced in our study are exceptional, and may be related to farmer expertise and investment in genetics and agronomy through on-farm and participatory research in Malawi and the region (Hermans et al., 2020; Snapp et al., 2018).

4.3. *Performance and stability in marginal environments*

Farmers must cope with fields that vary in quality and need to consider not just overall performance, but interaction with the environment and interaction with their livelihood system. We hypothesized that productivity of legume-maize systems would be buffered, whereas sole maize would be highly sensitive to environment: productive under mesic conditions and much less so under marginal conditions. This was rigorously tested by quantifying system performance for a wide range of weather, edaphic and management conditions; with 29 site-years that varied more than three-fold in terms of yield potential. There was a clear distinction among systems for stability by environment, with results that are consistent with our hypothesis, and an earlier report (Chimonyo et al., 2019). Unfertilized, sole maize produced about 1.8 T ha^{-1} 2 yr^{-1} in poor conditions, and about three times that in the high potential environments, consistent with maize production as being highly sensitive to environment (Setimela et al., 2017). This poses a challenge to food and income security of African smallholders who rely on maize for much of their calorie consumption.

The SI legume-maize systems performed much better than sole maize in the low and medium environments. This is consistent with promotion of grain legume rotations in Malawi to reduce risk under unfavourable conditions. However, it runs counter to an earlier assessment of food security risk associated with maize-pigeonpea systems which found poor grain yield performance at some sites and years in southern Malawi (Sirrine et al., 2010). The study reported on here was carried out over a wider area, with some sites tested over seven years, and included groundnut options, along with pigeonpea. Further, the technologies we tested benefited from years of participatory research that has been conducted on varieties, plant population densities, seeding arrangements, and rotational sequencing to fine-tune diversified SI maize (Mhango et al., 2013; Snapp et al., 2002; TerAvest et al., 2019).

Two lines of evidence presented here highlight that groundnut SI systems were outstanding producers of protein, as well as grain, even in marginal environments. This includes the coefficient of variation results and the AMMI biplot principal component scores for protein contribution in a low yielding environment. These were both consistent with high, stable performance for groundnut rotation and the DLR system in marginal environments. The effect of groundnut presence on yield quality and stability of performance has not been widely studied. However, a groundnut-maize rotation study was conducted at a very sandy site in Zimbabwe and found that groundnut and maize yield sequences could be maintained for twelve years (Waddington et al., 2007a). Further, the preference of farmers for groundnut in Malawi is often pronounced and stands out over all other grain legume options (Bezner Kerr et al., 2007; Mhango et al., 2013).

In addition to assessing crop species effect here, we considered rotational vs intercrop diversification. We hypothesized that rotational diversity would substantially enhance stability of crop yield, based on a country-wide set of demonstrations conducted across Malawi some time ago (Snapp et al., 2010). The findings reported here is the first evidence we know of based on dozens of site-year combinations, with experimentation conducted on replicated, smallholder farm plots. Diversification of maize with leguminous crops conferred high stability: a CV of 36% was associated with grain yield in rotation SI systems across all environments, a CV of 41% in a maize-pigeonpea intercrop, and a CV of 62% in unfertilized, sole maize. A three-year, multi-site study in

Zimbabwe did not test rotation diversification, but it did find marked stability was associated with a maize-cowpea intercrop compared to continuous maize (Madembo et al., 2020). The benefits of stability in a variable environment have been overlooked in many studies, yet smallholder farmers frequently face risky environmental conditions. This resilience property deserves greater attention in the literature.

4.4. Economics

The economic analysis conducted here highlighted that unfertilized maize is a poor performing system, which is consistent with earlier reports (Ngwira et al., 2012; Snapp et al., 2018). However, gross margin performance varies with prices, and with fertilizer application. Fertilizer prices often vary markedly, and policy makers must consider the potential for high grain output achieved through fertilized maize (Komarek et al., 2018), although this is not always realized on-farm (Burke et al., 2020). The intensified systems of fertilized, sole maize were equivalent to SI systems in this study, but it can be the highest overall performer. This was shown in two previous profitability studies based on simulated crop yield results, which found that fertilized maize consistently outperformed legume diversified systems in Malawi (Franke et al., 2014; Komarek et al., 2018). Groundnut rotation was more profitable than continuous maize in one study based on crop simulation model outputs; however, the price used for groundnut grain was very high as it was based on a shelled product (Komarek et al., 2018).

Pigeonpea systems were associated with modest costs in our study, and required minimal fertilizer use, so may be suited for farmers in marginal sites who have limited access to fertilizer. In the central region of Malawi farmers cultivate an average of ~0.85 ha, for a household size of 5 persons (Mungai et al., 2016). Maize-cowpea and maize-pigeonpea systems are well-suited in this area, and given the average household size crop yields from these systems meet household protein requirements (Smith et al., 2016). Thus maize-pigeonpea intercrops have been highlighted as the most economic and feasible SI option (Rusinamhodzi et al., 2012). Yet, at the same time, few farmers grow pigeonpea in Central Malawi, which stands in contrast to Southern Malawi. Farmers face constraints to pigeonpea production, such as poor market infrastructure and few livestock control systems in place (Waldman et al., 2017; Zulu et al., 2018).

4.5. Overall performance

Overall, performance was superior for legume SI systems over unfertilized sole maize. This is shown particularly in terms of performance in marginal environments and stability of production. This stands in contrast with smallholder adoption of legume crops in the region, which is limited, or in some cases, highly variable (Mhango et al., 2013; Silberg et al., 2017). There are, however, many farmer constraints to adoption of legume intercrops and rotational systems, including market access limitations, agronomic challenges, and knowledge gaps (Snapp et al., 2002; Waldman et al., 2017). The role of the SI systems in soil fertility enhancement remains incompletely understood, and we found no evidence for soil organic carbon gains associated with the presence of pigeonpea or groundnut. The high proportion of sandy sites in our on-farm long-term trials may have posed a challenge to detecting soil organic matter accrual.

A standout species within the SI technologies was groundnut, as this species was present in the systems which produced the most protein: the groundnut rotation and the DLR. Farmers interested in high and stable generation of protein who can afford groundnut seed costs may find the groundnut-based SI systems the most suitable, with consistently high profitability in this study. However, the suitability of pigeonpea SI options was also observed, particularly for the most cash-constrained farmers, whereas groundnut diversification had benefits for a range of environments, including marginal areas, but only for farmers who can afford the seed. This supports policies and recommendations that take into account farmers resources as well as environmental context.

5. Conclusion

The result from this paper highlights the benefits of diversifying groundnut with maize in different environments by comparing the yields, protein, stability, and profits. The performance of legume SI systems were particularly superior in marginal environments over sole maize systems. Legume systems with groundnuts in particular stood out with higher yields despite the significant costs, high protein contribution, rotation systems being more profitable and more stable. The SI systems with groundnut are most suitable and profitable than other systems for farmers interested in high and stable generation of income and protein at modest fertilizer costs.

Farmers in Malawi are engaged in intensifying maize production through fertilizer use and planting of modern maize varieties, widely subsidized by the Malawi government. Fertilizer efficiency appears to be under threat and there is an urgent need to understand which SI systems could be promoted for more consistent production of highly nutritious products. Our study highlighted the challenges associated with detecting improvements in soil properties, particularly for sandy sites. At the same time, we found that sufficient grain and protein can be produced under the variable conditions imposed by weather, management, and soil types. Through this multi-site and multi-year on-farm study, we found that promotion of groundnut systems could reduce agronomic and economic risk on marginal farm sites. Taken together, these findings draw attention to the need for agricultural policies that increase access of farmers to superior legume seeds and agroecology-based advice, and the need for further research on soil organic matter accrual.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107585.

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