Agricultural Systems 162 (2018) 77–88

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

# Maize yield and profitability tradeoffs with social, human and environmental performance: Is sustainable intensification feasible?

Sieglinde S. Snapp[a,b,*], Philip Grabowski[a,b], Regis Chikowo[a,b], Alex Smith[a], Erin Anders[a], Dorothy Sirrine[a], Vimbayi Chimonyo[a], Mateete Bekunda[c]

[a] Plant Soil and Microbial Sciences Department, Michigan State University, 1066 Bogue St A286, East Lansing, MI 48824, USA
[b] Center for Global Change Science and Earth Observations, Michigan State University, 1066 Bogue St A286, East Lansing, MI 48824, USA
[c] International Institute of Tropical Agriculture (IITA), c/o AVRDC, The World Vegetable Center, P.O. Box 10, Duluti, Arusha, Tanzania

## ARTICLE INFO

*Keywords:*
Indicators
Sustainable intensification
Causal loop
Tradeoffs
Legume

## ABSTRACT

Sustainable intensification (SI) has been regarded as the basis for environmentally sound and equitable agricultural development. Field based assessment of technologies needs to move beyond production and economic performance to include environment, social and human condition. In this study we systematically consider all five domains of SI based on participatory action research (PAR) initiated in 2012 at three Central Malawi sites that varied in agroecology from low to high potential. Fifteen SI indicators were assessed for four technologies: sole maize (*Zea mays* L.) with 0 and recommended fertilization (69 kg N $ha^{-1}$ and 9 kg P $ha^{-1}$), pigeonpea (*Cajanus Cajun* (L.) Millsp.)-maize intercrop (half rate fertilizer), and doubled up legume rotation (DLR, a pigeonpea-groundnut intercrop) sequenced with maize at half rate fertilizer in that phase. Through radar charts SI performance and tradeoffs were visualized, and causal loop analysis allowed identification of research gaps. SI indicator assessments included crop performance from on-farm trials, profitability, modeled probability of food sufficiency, risk of crop failure and ratings of technologies by women farmers who were engaged in evaluation of technologies through participatory research. The PAR included six mother trials, 236 baby trial farmers and a survey that was carried out with 324 farmers (baby trial farmers plus control farmers) to document socio-economic factors and management practices on focal fields. Replicated mother trials further provided the basis for simulation modeling (APSIM) of weather-associated crop failure risk and slow processes such as soil carbon (C) accrual. Radar charts were used to visualize SI performance of the technologies. Environmental performance of the two pigeonpea-diversified technologies was variable, but generally high compared with sole maize systems, due to gains in vegetative biomass, duration of cover and biological nitrogen (N) fixation. Maize production and economic assessment varied by site, and with steeper tradeoffs for legume diversification in the mesic site, less so in the marginal site. The domains of social and human capacity building were superior for legume integration, notably in terms of diverse diet, food security and farmer preferences (notably, female farmers generally favored legume crops). Performance varied by site with legume systems most beneficial at the most marginal site, including less risk of crop failure than unfertilized maize. Causal loop analyses identified regulators of SI that require further attention, notably: crop-livestock conflicts and opportunities, male-female control of legume crop production, and residue management. Overall, the SI indicators framework provided a systematic means to consider tradeoffs and opportunities associated with novel crop combinations and management practices.

## 1. Introduction

Sustainable intensification (SI) has been put forward as the pathway to address global requirements for food, fuel and fiber production, while simultaneously protecting environmental services and conserving resources. The nature and scope of SI, however, is highly contested (Gunton et al., 2016). Initial definitions put forward for SI focused primarily on agronomic production, profitability and protecting the environment (Baulcombe et al., 2009; Tilman et al., 2002). Recently there have been important efforts to broaden the definition of SI to include social aspects such as gender equity and human capacity (Godfray, 2015; Pretty et al., 2011; Loos et al., 2014). The scope

---

* Corresponding author.
*E-mail address:* snapp@msu.edu (S.S. Snapp).

https://doi.org/10.1016/j.agsy.2018.01.012
Received 22 April 2017; Received in revised form 12 December 2017; Accepted 15 January 2018

encompassed by SI is becoming broader, as the science of sustainability is maturing and multidisciplinary approaches are coming to the fore (Gunton et al., 2016; Petersen and Snapp, 2015).

### 1.1. Framework for SI indicators

We apply a SI framework here that considers indicators for five domains, namely: production, economics, environment, social and human condition ((http://www.k-state.edu/siil/resources/index.html). This framework was developed through a systematic process led by a steering committee with participants from eight institutions and multidisciplinary perspectives from human and natural sciences, including economists, soil scientists, modelers, agronomists, nutritionists, gender specialists and livestock scientists (Smith et al., 2017). The domains were identified so as to explicitly consider multiple and sometimes contradictory SI objectives such as increasing yields, increasing income, improving the natural resource base, reducing inequity and improving food security, with the aim of supporting research in sustainable development. Identification of SI indicators for the framework took into account cost-effective, and practical, means for research in development teams to support cyclic, co-learning processes and consideration of tradeoffs over time. Through this framework we aim to move beyond linear, project defined considerations, to iteratively engage with farmers, educators, communities, policymakers, and other stakeholders (Bell and Morse, 2004; Falconnier et al., 2017; Snapp et al., 2002a).

The literature on SI assessments provides few examples of practical applications using field based action research data to evaluate technologies in multiple domains. A climate-smart agricultural assessment framework has been applied to livestock systems innovation, with consideration given to the domains of productivity, adaptation, and mitigation, and indicators used in a participatory, iterative process (Notenbaert et al., 2017). Interestingly, simple educational initiatives, rather than complex climate smart agricultural technologies, were the best performers in all three domains in this earlier study. We found few such examples and seek to fill this gap. Policy makers, scientists, and extension educators urgently need examples of how to identify technologies and visualize relative SI performance across multiple domains, while taking into consideration relevance to farmers preferences.

### 1.2. Malawi context

The application of a SI indicators framework is explored here by assessing Malawian agriculture through an Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) participatory action research (PAR) project (Mungai et al., 2016). Malawi is dominated by smallholder maize (*Zea mays)*-based mixed farming systems, with population density on the rise and intensification processes underway (Jayne et al., 2014). This context provides an opportunity to explore SI processes within a maize-based rain-fed system that is important across Africa to over 200 million smallholders (Blackie and Dixon, 2016). Soil fertility is a key productivity-limiting factor on smallholder farms throughout the country, and fertilizer subsidies have been promoted widely as a means to address this challenge (Chirwa and Dorward, 2013). Fertilizer use has been promoted through subsidy programs and policies that have increased access from about 30% of farmers (as documented in a 1999 survey of sites near the study area; Snapp et al., 2002b) to 76–92% of farmers in the current study area (Mungai et al., 2016). However, the sustainability of this approach is contested, both in terms of the economic implications of reliance on externally-funded access to fertilizers, and the extent to which the soil resource base can sustain continuous production of maize.

Malawi farming systems are representative of high population density locations in Southern and Eastern Africa, with limited livestock population densities, a narrow range of crops grown and farms less than 1.0 ha in size (Jayne et al., 2014). Almost all farmers grow maize, and generally a small portion of farmland is dedicated to a food legume and or cash crop (Snapp et al., 2002b). Degradation of soil resources may be the basis for remote sensing observations of negative trends in net primary productivity on agricultural lands (Messina et al., 2017). There is urgent need for sustainable agricultural practices to reverse this trend.

### 1.3. SI technology options

Africa RISING Malawi is testing legume ‘best bet’ species and recommended varieties, grown in mixtures or sequenced with maize combined with an integrated soil fertility management (ISFM) strategy, to sustainably improve crop yields, while paying attention to local priorities (Snapp et al., 2002a; Bezner-Kerr et al., 2007; Mhango et al., 2013). Farmer-engagement and co-learning on SI technologies has been promoted in Malawi since 1996, with an initial focus on agroforestry that has evolved to emphasize multipurpose legumes combined with targeted fertilizer use. Technologies were identified as best bet options based on criteria that included yield, profitability and potential to protect the environment, tested in country-wide trials and site-specific PAR (Snapp et al., 2010). The SI framework provides an opportunity to take this research to the next level and assess performance across a broader, more holistic set of sustainability goals.

The objective of this study is to assess the value of applying a practical SI indicator framework to evaluate maize-legume diversification and ISFM technologies. The assessment of technologies includes: 1) evaluation of performance in rain-fed maize systems, in terms of agronomic, economic, environmental, social and human dimensions; 2) analysis of trade-offs using radar charts to visualize performance along multiple dimensions and 3) identification of research gaps and regulators of SI through causal loop diagrams.

## 2. Methods

### 2.1. Context

#### 2.1.1. Bio-physical environment

Central Malawi is characterized by tremendous variation in topography. A steep escarpment bisects Central Malawi, supporting intermixed agricultural areas of sub-humid, uni-modal rainfed upland maize-based cropping. The seasonal precipitation is 800 to 1100 mm with high inter-annual variation in quantity and in distribution (Table 1). The three research locations were chosen in a stratified randomized manner, with initial characterization of Central Malawi administrative areas (designated as extension planning areas, EPAs) into three levels of agricultural potential, low, medium and high, then random selection of an EPA to represent each level (Mungai et al.,

**Table 1**
Environmental and soil characteristics of three sites where Africa RISING has conducted participatory action research with farmers and Malawi extension since 2012, annual average rainfall and temperature based on weather stations (Mungai et al., 2016) and a soil characterization survey carried out on 220 farmer fields located in the project area.

| | Golomoti | Kandeu | Linthipe |
|---|---|---|---|
| Annual average rainfall (mm) | 884 | NA[a] | 875 |
| Elevation (meters above sea level) | 555 | 904 | 1238 |
| Mean minimum temperature (°C) | 13.3 | 10.8 | 7.8 |
| Mean maximum temperature (°C) | 32.4 | 29.9 | 27.7 |
| Top soil pH (mean, min-max) | 6.4 (5.6–7.5) | 6.3 (5.3–7.8) | 6.2 (5.6–6.9) |
| Soil P (ppm, mean, min-max) | 67.9 (9.4–139) | 19 (1–64) | 7.3 (1.8–38) |
| Sandy clay soils (%) | 41.1 | 37.4 | 74.7 |
| Sandy soils (%) | 58.1 | 61.9 | 7.0 |
| Clay or loamy soils (%) | 0.8 | 0.7 | 18.3 |

[a] Not available = NA. For comparison purposes, Annual Average Rainfall for this location based on a downscaled estimate = 866 mm (TRIMM, 2016).

2016). Low potential Golomoti has high evapotranspiration and poorly distributed rainfall, and is located at low altitude along the Lake Malawi lakeshore plain. Linthipe is a high potential site with generally well distributed rainfall and is located in the Lilongwe mid-altitude plain. Relative to the other two sites, medium potential Kandeu is intermediate in rainfall and growth potential and is located in the highly dissected landscape of the escarpment.

Agriculture in Central Malawi is primarily maize-based rainfed farming with cash crops such as tobacco (*Nicotiana tabacum* L.) or cotton (*Gossypium hirsutum* L.), and in some areas, a grain legume. Two soil types, Luvisols and Lixisols, are widely present in the project area, and across Malawi (22 and 26%, respectively) with good drainage characteristics, low to moderate fertility, and generally moderate acidity (Table 1; Dijkshoorn et al., 2016). Soil P levels are often below the critical level of 15 mg P kg soil$^{-1}$, soil organic matter status is generally low, which contributes to the presence of degraded agricultural lands (Li et al., 2017; Snapp, 1998).

#### 2.1.2. Socio-economic environment

We developed farm typologies by clustering farms on key farm resources (farm size, income sources, labor availability, livestock and other assets) and variables related to production objectives and market orientation (the percent of income from crop sales, and the percent of household expenditure on food). Initial analysis showed two functional groups for technology targeting: 1) a small number (16%) of resource endowed large farms– that derive most of the income on-farm, and 2) a wide band of resource poor farms with (74%) that rely on both on-farm and off farm income (Chikowo et al., 2018). Larger farms are better positioned to invest in mineral fertilizers and growing maize sequenced with grain legumes, either as sole crops or intercropped with another legume as a doubled up legume rotation (DLR). In contrast, small farms could use low input combinations of maize-legume intercrops and DLR. The third group of farmers (10%) focuses on off-farm activities and are not likely to relate well with any of the SI technologies.

### 2.2. Participatory action research for SI farming systems

The Africa RISING program started in 2012 in Central Malawi, with site selection, training in PAR approaches and SI technology options (Mungai et al., 2016). Participatory research on best bet SI options was based on a mother and baby trial design (Snapp et al., 2002a). This involved centrally located, on-farm 'mother trial' located in two communities at each of the three project locations for a total of six mother trials (Fig. 1). Full suites of SI options were tested at mother trials, encompassing ten to twelve technologies, replicated three times. About sixty farmers in the surrounding community with each mother trial carried out baby trials to experiment with farmer-chosen subsets of technologies. This approach supports engagement of farmers in trying out and adapting SI technologies on baby trial plots, including spacing, seeding rates and combinations of crops and soil amendments (Johnson et al., 2003; Snapp et al., 2002a).

The full suite of technologies evaluated in the mother trials included maize grown at different fertilizer rates, manure and fertilizer applied to maize, intensified soybean (*Glycine* max L.) production (double rows, inoculum and micro-dosing of fertilizer), and maize intercropped with pigeonpea (*Cajanus cajan* (L.) Millsp.), and sequenced with a DLR, pigeonpea grown with an understory grain legume species (Snapp et al., 2010; Van Vugt et al., 2016). Two SI technologies that included

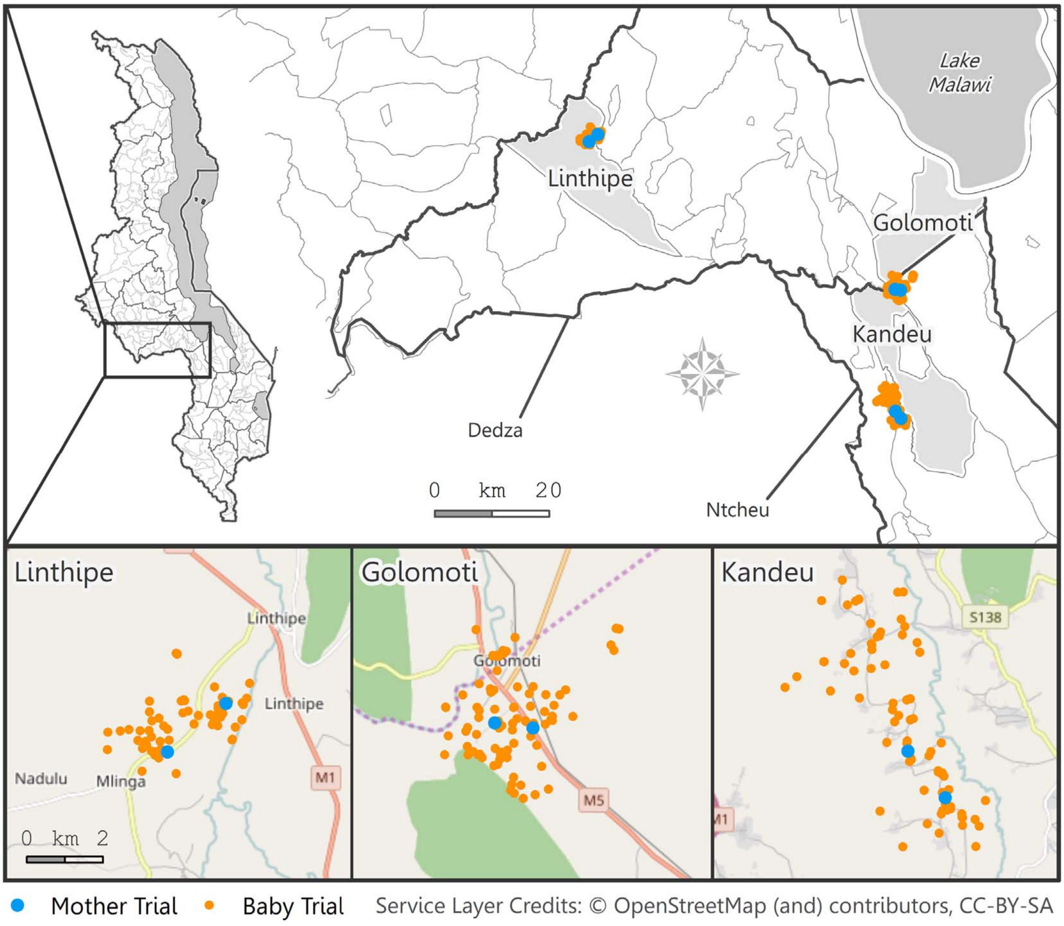

**Fig. 1.** Central Malawi Africa RISING sites in Golomoti, Kandeu and Linthipe. Baby trial locations shown as orange dots and mother trial locations as blue dots (http://globalchangescience.org/eastafricanode/) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

**Table 2**
'Best bet' maize-legume ISFM technology options for SI experimentation at Africa RISING sites. Characteristics shown in terms of agro-ecological traits, plant life form diversity, number of food crops present and farmer assessment.
Adapted from Snapp et al., 2010). Fertilizer rate per recommended practice, on an annualized basis, Malawi Guide to Agriculture, MAFS, 2012.

| Technology | Option | Life forms | Months cover[a] | Food crops | Fertilizer kg/ha | Farmer Rating[b] |
|---|---|---|---|---|---|---|
| Sole maize without fertilizer | Mz0 | Annual grass | 4 | 1 | 0 N<br>0 P | 1.0 |
| Sole maize full fertilizer | MzNP | Annual grass | 4 | 1 | 69 N<br>9 P | 2.5 |
| Pigeonpea-maize intercrop ½ fertilizer | PP-Mz | Shrub legume | | | | 2.7 |
| | | Annual grass | 9 | 2 | 34.5 N<br>4.5 P | |
| Doubled up legume/maize rotation ¼ fertilizer | DLR | Shrub legume | | | | 3.2 |
| | | Annual legume | 6.5 | 3 | 17.3 N | |
| | | Annual grass | | | 2.3 P | |

[a] Months of cover shown an annualized basis, divided by two for 2-year rotation.

[b] Farmer rating based on farmer survey conducted in 1998, where n = 30, scale 1 = poor, 2 = moderately poor, 3 = moderately good, 4 = good (Snapp et al., 2010).

pigeonpea were chosen for a detailed SI assessment in this study, and systematically compared with fertilized and unfertilized maize for a total of four technologies (Table 2). Pigeonpea is grown in Southern Malawi, but it is a novel crop in the Central and Northern region of Malawi (Peter et al., 2017). It was chosen based on its unique properties that support multiple services, such as longevity of growth, high biological nitrogen fixation capacity, superior fodder material, and production of peas that can be consumed or sold (Mhango et al., 2013; Orr et al., 2015). Preliminary evaluations conducted in the late 1990s indicated the potential of pigeonpea to address multiple environmental and food security objectives; however, farmer acceptance varies across Malawi, and lags in many areas (Snapp et al., 2002a, 2003; Waldman et al., 2016).

Pigeonpea integration within Malawi cropping systems has been focused on intercrops with maize. A novel approach evaluated here is the DLR which involves the complementary growth habit of a slow growing pigeonpea crop (5 to 8 month maturity) and a fast growing understory crop such as groundnut (*Arachis hypogaea* L.) that matures in about 4 months, or other annual pulses such as soybean, see http://globalchangescience.org/eastafricanode/index.php/innovations/). The attributes of the technologies and farmer ratings from earlier PAR in Malawi are shown in Table 2.

The full rate fertilizer application used for maize is based on the Malawi government recommendation and provides 9 kg P ha$^{-1}$ and 69 kg N ha$^{-1}$, with P applied at planting and N applied in a split manner, at planting and about one month after crop emergence (MAFS, Malawi Guide to Agriculture, 2012). All crops are grown following recommended planting arrangements, with ridges prepared by hand-hoe, 0.75 cm between ridges, and in-row spacing appropriate to the crop species planted, as indicated below:

- Maize: seeding at 25 cm within row spacing for a plant population of 53,000 plants ha$^{-1}$.
- PP-Mz intercrop: Seeding 3 plants per station of pigeonpea at 90 cm in-row located in the same row half way between maize planting stations at the same spacing and seeding rate; Both crops have populations of 44,000 plants ha$^{-1}$ for a total of 88,000 plant ha$^{-1}$
- DLR rotated with maize: Groundnut planted at a spacing of 9 cm in-row in the space between the pigeon pea plants at 79,000 plants ha$^{-1}$ (90% additive design). Pigeonpea population at 44,000 ha$^{-1}$. Maize rotation phase in year two equals sole maize plant population density.

### 2.3. SI indicators assessment

The analysis of SI indicators was carried out to assess how two of the most promising technologies (PP-Mz intercrop and DLR) compared with two conventional maize systems (continuous sole maize with and without fertilizer) across the five SI domains. The introduction of a new semi-perennial crop, pigeonpea, posed unique challenges due to uncontrolled grazing that limited our ability to measure yield potential, and this required using a combination of model and field-experimentation based indicators. This is a less than ideal approach as these involve different types of metrics. However, many SI technologies rely on introducing long duration vegetative cover species in order to sustain resources, and we present this example of a mixed methods approach as an imperfect but practical means to address the challenges posed in on-farm research where there are issues such as changing norms in livestock control.

We selected indicators relevant to this objective and constructed radar charts and a causal loop diagram to identify the most important direct and indirect consequences of the legume systems across the five domains, which is presented in the discussion. Data gaps and the assumptions used in the analysis are also discussed. The following sections outline how the various SI indicators were assessed.

#### 2.3.1. Agronomic performance and environmental impacts

Crop yields were evaluated on the six 'mother trials', two trials located at each of the project sites, implemented over three growing seasons, 2012–13, 2013–14, and 2014–15, for a total of 2 × 3 × 3 = 18 site-years. Mother trials included three replicates per site, with plots sized 6 m × 4 m. Maize and groundnut yields were measured in May of each year by harvesting net plots (5 m × 2.25 m), and two smaller randomly situated net plots per plot were used to measure pigeonpea biomass and grain yield in July. Maize grain moisture from the net plot was determined using a moisture meter, and all grain yields are reported at 12.5% moisture content (Smith et al., 2016). Residue biomass was collected from the net plot, and weighed in the field to determine fresh weight of samples and subsamples. Pigeonpea grain yields were almost always damaged by livestock grazing so these were modeled using APSIM as described below (and see Ollenburger and Snapp, 2014), after calibration of APSIM with pigeonpea data from the sites and years where it was possible to measure performance. Calibration involved the model being run for the three sites using meteorological data from 1980 to 2005 to estimate the long-term consequences of continuous use of each of the technologies, e.g., change over time for organic C and total N expressed as percent change relative to initial conditions (APSIM Initiative, 2013; Holzworth et al. 2014). We followed mother trial management practices in APSIM simulations, such as incorporation of three-quarters of crop residues, removal of remainder, and moderate N fertilizer doses as shown in Table 2; these were designed to be representative of farming in the study area, based on survey data (Mungai et al., 2016).

Further calibration was carried out for this study based on pigeonpea grain from mother trial field experimentation 2015–2017, with good agreement between observed and predicted (RMSE = 159). Hence, model outputs for 2013–14 and 2014–15 were deemed satisfactory for use in this study (Fig. S1). We note that this model has been extensively calibrated for Malawi soil types and crop varieties (Robertson et al., 2005).

The diversity added to the cropping system through the legumes has several potential environmental benefits, including months of living cover and associated living roots that provide habitat for microorganisms and enhance soil health, as well as prevent erosion. Fossil-fuel conservation is indicated by efficient maize response to N fertilizer (through rotational diversity and biological N fixation) (Table 2).

### *2.3.2. Economics*

We calculated net income to assess the profitability of each technology at the three research sites. We used the actual input and yields from the mother trials in the calculations. Labor costs were not included due to lack of data on total labor requirements for each system and due to the complexity of appropriately valuing the opportunity cost of household labor. Associated input/output prices for maize grain, pigeonpea and groundnut were based on a combination of prices received by farmers as reported in the 2013 baseline survey (unpublished data, see survey description in Mungai et al., 2016), and from the project's monitoring of markets in these locations. Prices were kept constant by location, and a sensitivity analysis was carried out by including two price scenarios: one with average maize price ($0.21/kg) and average legume prices to estimate the most likely profitability of these systems and one with a high maize price ($0.45/kg, which a farmer may obtain by storing the harvest for six months or more) and a low price for the legumes (which could be possible if supply increased dramatically). Values for all prices are listed in Supplementary Table S1.

We also calculated returns to fertilizer in terms of maize production per elemental N applied as synthetic fertilizer. This is referred to as partial factor productivity from applied N fertilizer ($PFP_N$) in the literature (Cassman et al., 2002). This is an important consideration for farmers who have limited resources to purchase fertilizer. Due to seasonal fluctuation in prices we presented the returns in terms of grain production per fertilizer N; $PFP_N$ which is also a metric of efficient use of applied fertilizer. Conservation of fertilizer N is key to preservation of scarce fossil fuel resources and limiting greenhouse gas emissions from agriculture (Robertson and Vitousek, 2009).

### *2.3.3. Food security and gender equity*

Increased availability of legume grain produced could contribute to improved family nutrition, and although testing this was beyond the scope of the study, a seminal study in Asia points in this direction (Darmadi-Blackberry et al., 2004). As described in Smith et al. (2016), we used modeled yield results based on an average farm size per site, and 100% adoption of a technology to estimate the probability of a household producing all the calories and protein that it needed, as a metric related to food security. Mean household demographics and farm size was based on survey data from the project's baseline (Mungai et al., 2016), and used to calculate calorie and protein requirements. We also used weather series and simulation modeling to predict failed maize harvest (less than 33% of the mean harvest) for each system over the simulation period to demonstrate the riskiness of the technology. These are indicators that are practical to estimate, based on data generated through PAR with farmers, linked to crop modeling, in a manner typical of many agronomic research in development projects.

As an indicator to evaluate potential gender equity implications of the technologies, we report the percent of female farmers who tested the legume technologies and preferred them to sole maize systems. This indicator is straight forward to assess and can be used as a means to take into consideration the views of a group that is often marginalized. The data was collected in a July 2014 survey of 236 baby trial farmers that documented pairwise rankings of technologies (not all farmers tested all technologies). The results were gender disaggregated, and we report the percent of farmers who preferred PP-Mz and DLR over sole maize, and maize to PP-Mz.

## 3. Results

The data for each of the SI indicators are presented separately by site, due to important interactions with agro-ecology (Tables 3–5). The results are presented visually as radar charts to facilitate comparison of the technologies across the five domains (Figs. 2–4), to identify technology candidates to implement on farms, and promote through policy.

### *3.1. Productivity of the land*

At all sites, unfertilized sole maize yields were very low and fertilized maize were high. Sole maize was responsive to environment, where grain yield was highest at the mesic Linthipe site (Table 3 and Fig. 2), and lowest at the marginal Golomoti site (Table 5 and Fig. 4). Maize yields from the PP-Mz intercrop were maintained at high levels,

**Table 3**
Indicators for sustainable intensification for four technologies at Linthipe, Malawi.

| Indicators by domain | Units | Maize0 | MaizeNP | PP-Mz | DLR | Data sources |
|---|---|---|---|---|---|---|
| Productivity | | | | | | |
| Maize yield[a] | kg/ha | 1087 | 5908 | 4536 | 2567 | Mother trial – 3 years |
| Maize residues | kg/ha | 3845 | 10,051 | 6935 | 4653 | Model average - 25 yrs. |
| Legume residues | kg/ha | 0 | 0 | 4279 | 4949 | Mother trials and APSIM model |
| Legume yield (total) | kg/ha | 0 | 0 | 487 | 792 | Combined |
| Pigeonpea yield | kg/ha | 0 | 0 | 487 | 282 | Modeled avg. - 25 years |
| Groundnut yield[b] | kg/ha | 0 | 0 | 0 | 511 | Mother trials – 3 years |
| Economic | | | | | | |
| Profitability – avg. prices | $/ha | $205 | $1118 | $1028 | $841 | Prices from surveys |
| Profitability – high maize price | $/ha | $470 | $2560 | $2031 | $1280 | Maize price at seasonal high |
| Partial factor productivity of nitrogen fertilizer | kg maize/kg N | n.a. | 86 | 146 | 195 | Mother trial – 3 years |
| Environment | | | | | | |
| Months of soil cover | Month | 5 | 5 | 9 | 9 | Pigeonpea duration |
| Soil carbon - relative change | % change | −10.8% | −7.5% | −0.3% | −3.0% | Modeled 25-year simulation (APSIM) |
| Annual change in soil carbon | change in % C | −0.00964 | −0.00665 | −0.00031 | −0.00266 | Modeled % of soil dry mass (top 15 cm)- APSIM |
| Soil N - relative change | % change | −10.6% | −6.7% | 1.3% | −2.3% | Modeled 25-year simulation (APSIM) |
| Soil N – end value of 25-yr simulation | Total soil N - % mass | 0.1158 | 0.1208 | 0.1314 | 0.1277 | Modeled % of soil dry mass (top 15 cm)- APSIM |
| Human condition | | | | | | |
| Probability of food sufficiency | % | 12% | 96% | 92% | 100% | Modeled based on survey data |
| % years without crop failure | % | 92% | 96% | 100% | 100% | Modeled avg. - 25 years |
| Social | | | | | | |
| Gender (women preferring system)[c] | % farmers | 33% | 33% | 67% | 50% | Pairwise ranking (n = 46) |
| Farmers preferring system | % farmers | 33% | 33% | 67% | 60% | Pairwise ranking (n = 69) |

[a] n = 18 for all but DLR, whose n = 6; Least significant difference across sites, systems and seasons = 875.7.

[b] n = 6; Least significant difference across sites and seasons = 735.7.

[c] For all pairwise rankings maize compared with PP-Mz, legumes systems compared with Mz.

**Table 4**
Indicators for sustainable intensification for four technologies at Kandeu, Malawi.

| Indicators by domain | Units | Maize0 | MaizeNP | PP-Mz | DLR | Data sources |
|---|---|---|---|---|---|---|
| Productivity | | | | | | |
| Maize yield[a] | kg/ha | 1003 | 5018 | 4253 | 1742 | Mother trial – 3 years |
| Maize residues | kg/ha | 3583 | 9975 | 6943 | 4854 | Model average - 25 yrs. |
| Legume residues | kg/ha | 0 | 0 | 6573 | 5496 | Mother trials and APSIM model |
| Legume yield (total) | kg/ha | 0 | 0 | 751 | 858 | Combined |
| Pigeonpea yield | kg/ha | 0 | 0 | 751 | 492 | Modeled avg. - 25 years |
| Groundnut yield[b] | kg/ha | 0 | 0 | 0 | 367 | Mother trials – 3 years |
| Economic | | | | | | |
| Profitability – avg. prices | $/ha | $188 | $935 | $1054 | $637 | Prices from surveys |
| Profitability – high maize price | $/ha | $432 | $2159 | $1932 | $866 | Maize price at seasonal high |
| Partial factor productivity of N fertilizer | kg maize/kg N | n.a. | 72.7 | 145.1 | 150.7 | Mother trial – 3 years |
| Environment | | | | | | |
| Months of soil cover | Month | 5 | 5 | 9 | 9 | Pigeonpea duration |
| Soil carbon - relative change | % change | − 5.9% | 1.7% | 11.2% | 10.0% | Modeled 25-year simulation (APSIM) |
| Annual change in soil carbon | change in % C | − 0.00238 | 0.00067 | 0.00453 | 0.00405 | Modeled % of soil dry mass (top 15 cm)- APSIM |
| Soil N - relative change | % change | − 5.3% | 3.5% | 14.3% | 12.6% | Modeled 25-year simulation (APSIM) |
| Soil N – end value of 25-yr simulation | Total soil N - % mass | 0.0712 | 0.0778 | 0.0860 | 0.0852 | Modeled % of soil dry mass (top 15 cm)- APSIM |
| Human condition | | | | | | |
| Probability of food sufficiency | % | 35% | 100% | 85% | 100% | Modeled based on survey data |
| % years without crop failure | % | 92% | 96% | 96% | 96% | Modeled avg. - 25 years |
| Social | | | | | | |
| Gender (women preferring system)[c] | % farmers | 67% | 67% | 33% | 43% | Pairwise ranking (n = 55) |
| Farmers preferring system | % farmers | 57% | 57% | 43% | 42% | Pairwise ranking (n = 82) |

[a] n = 18 for all but DLR, whose n = 6; Least significant difference across sites, systems and seasons = 875.7.

[b] n = 6; Least significant difference across sites and seasons = 735.7.

[c] For all pairwise rankings maize compared with PP-Mz, legumes systems compared with Mz.

**Table 5**
Indicators for sustainable intensification for four technologies at Golomoti, Malawi.

| Indicators by domain | Units | Maize0 | MaizeNP | PP-Mz | DLR | Data sources |
|---|---|---|---|---|---|---|
| Productivity | | | | | | |
| Maize yield[a] | kg/ha | 363 | 3543 | 3197 | 1993 | Mother trial – 3 years |
| Maize residues | kg/ha | 2127 | 8217 | 8218 | 4015 | Model average - 25 yrs. |
| Legume residues | kg/ha | 0 | 0 | 2855 | 3145 | Mother trials and APSIM model |
| Legume yield (total) | kg/ha | 0 | 0 | 326 | 796 | Combined |
| Pigeonpea yield | kg/ha | 0 | 0 | 326 | 172 | Modeled avg. - 25 years |
| Groundnut yield[b] | kg/ha | 0 | 0 | 0 | 624 | Mother trials – 3 years |
| Economic | | | | | | |
| Profitability – avg. prices | $/ha | $56 | $631 | $701 | $767 | Prices from surveys |
| Profitability – high maize price | $/ha | $145 | $1496 | $1411 | $1061 | Maize price at seasonal high |
| Partial factor productivity of N fertilizer | kg maize/kg N | n.a. | 51.3 | 102.1 | 161.7 | Mother trial – 3 years |
| Environment | | | | | | |
| Months of soil cover | Month | 5 | 5 | 9 | 9 | Pigeonpea duration |
| Soil carbon - relative change | % change | − 9.8% | − 1.4% | 2.7% | 2.4% | Modeled 25-year simulation (APSIM) |
| Annual change in soil carbon | change in % C | − 0.00322 | − 0.00046 | 0.00089 | 0.00078 | Modeled % of soil dry mass (top 15 cm)- APSIM |
| Soil N - relative change | % change | − 9.3% | 0.3% | 5.0% | 4.6% | Modeled 25-year simulation (APSIM) |
| Soil N – end value of 25-yr simulation | Total soil N - % mass | 0.0558 | 0.0618 | 0.0647 | 0.0651 | Modeled % of soil dry mass (top 15 cm)- APSIM |
| Human Condition | | | | | | |
| Probability of food sufficiency | % | 0% | 92% | 85% | 92% | Modeled based on survey data |
| % years without crop failure | % | 62% | 88% | 88% | 88% | Modeled avg. - 25 years |
| Social | | | | | | |
| Gender (women preferring system)[c] | % farmers | 20% | 20% | 80% | 50% | Pairwise ranking (n = 43) |
| Farmers preferring system | % farmers | 17% | 17% | 83% | 25% | Pairwise ranking (n = 90) |

[a] n = 9 for all but DLR, whose n = 3; Least significant difference across sites, systems and seasons = 875.7.

[b] n = 6; Least significant difference across sites and seasons = 735.7.

[c] For all pairwise rankings maize compared with PP-Mz, legumes systems compared with Mz.

although not quite as high as fertilized sole maize. In addition to maize grain, the PP-Mz intercrop has the potential to produce an additional crop, of a nutrient-dense pigeonpea grain that may fetch a higher price than maize (but not in all cases).

The DLR is sequenced as follows: pigeonpea-groundnut intercrop is produced before maize, so only one year in two has a maize crop. Thus, on an annualized basis maize grain yields were modest (where annualized maize is a metric closely related to food security on farms with small landholdings; see Droppelmann et al., 2017). At the same time, DLR produced the largest amount of combined yields (from maize plus legume crops), and this grain production required modest fertilizer inputs (one-quarter rate, on an annualized basis). The ∼800 kg of

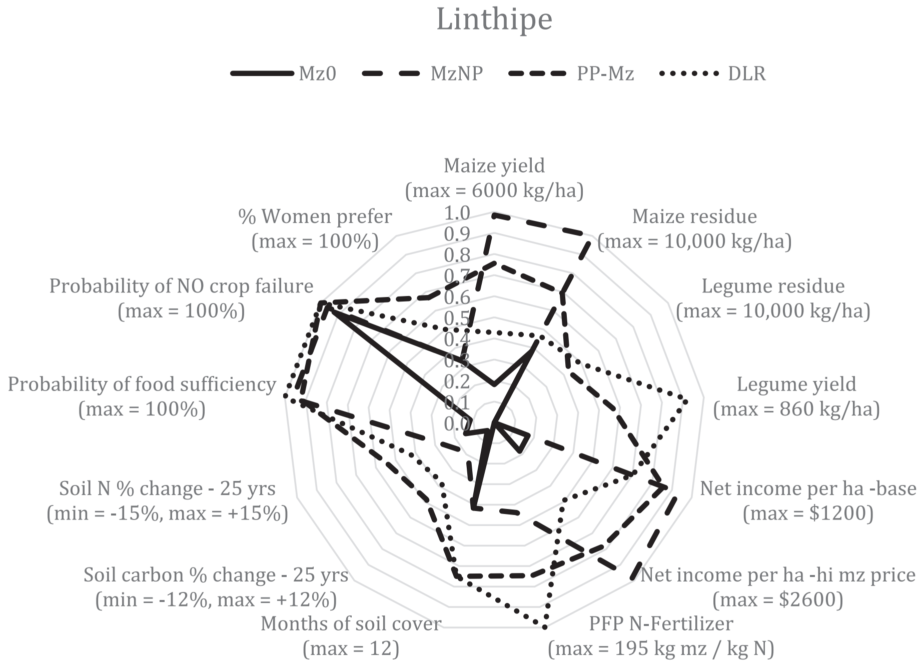

**Fig. 2.** Indicators of sustainable intensification for legume systems (pigeonpea-maize intercrop half-rate NP fertilizer = PP-Mz and doubled up legume rotation of pigeonpea-groundnut rotated with maize = DLR) and sole maize systems (unfertilized = Mz0 and full fertilizer MzNP), in Linthipe, Malawi. Crop and residue yields are reported on an annualized basis, i.e., halved for 2 year rotation DLR. Note: For specific values and details on data sources see Table 3.

legume grain $ha^{-1}$ that was produced annually by DLR was consistent across all sites, including the marginal as well as the high yield potential sites.

### 3.2. Economics

Net incomes were very low for unfertilized maize at all sites. For the other systems, there was a strong interaction with site: the three technologies had similar levels of net income at high potential Linthipe, whereas in moderate potential Kandeu the PP-Mz technology had the highest net income (Table 4 and Fig. 3) and in marginal Golomoti the DLR system had the highest. Returns to fertilizer were greater with systems that had a larger legume presence: $PFP_N$ varied from 50 to 85 kg grain kg $N^{-1}$ for continuous maize, from 100 to 145 for PP-Mz and was the highest for maize sequenced with DLR, from 150 to 194. Linthipe was associated with the highest $PFP_{N,}$ for each technology.

### 3.3. Environment

The technologies with long-lived legumes produced large amounts of legume biomass, and had substantially greater living coverage (~¾ of the year). In comparison, a sole maize system can produce large amounts of maize residues, but only has a living plant present for ~4 months (Tables 3–5). Environmental benefits through conservation of fertilizer include energy saved to produce the fertilizer, and preservation of water and air quality (Robertson and Vitousek, 2009). The amount of fertilizer required to support farming system productivity was halved through the introduction of a PP-Mz intercrop (fertilized at

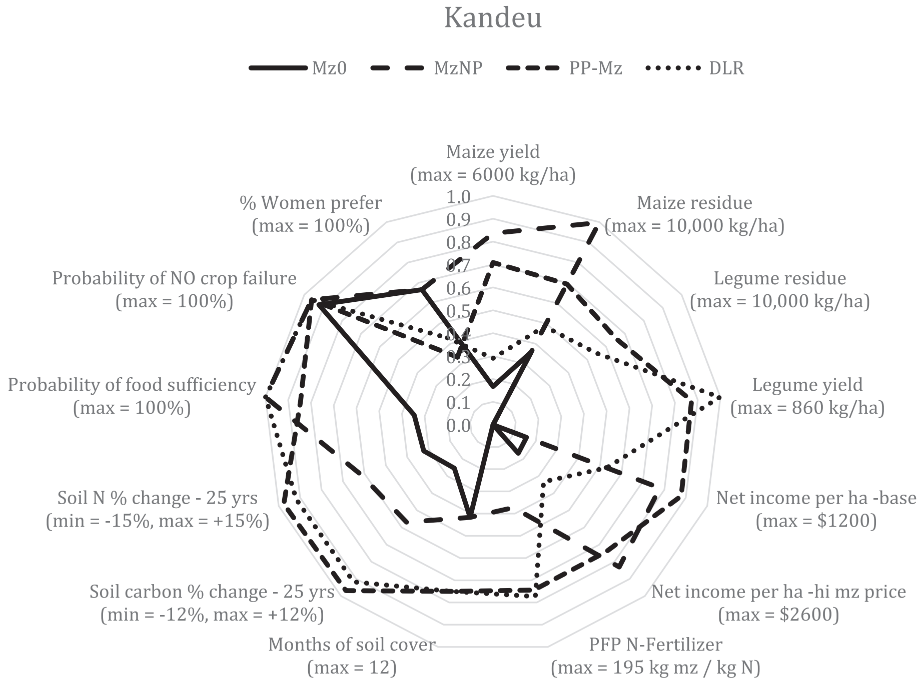

**Fig. 3.** Indicators of sustainable intensification for legume systems (pigeonpea-maize intercrop half-rate NP fertilizer = PP-Mz and doubled up legume rotation of pigeonpea-groundnut rotated with maize = DLR) and sole maize systems (unfertilized = Mz0 and full fertilizer MzNP), in Kandeu, Malawi. Crop and residue yields are reported on an annualized basis, i.e., halved for 2 year rotation DLR. Note: For specific values and details on data sources see Table 4.

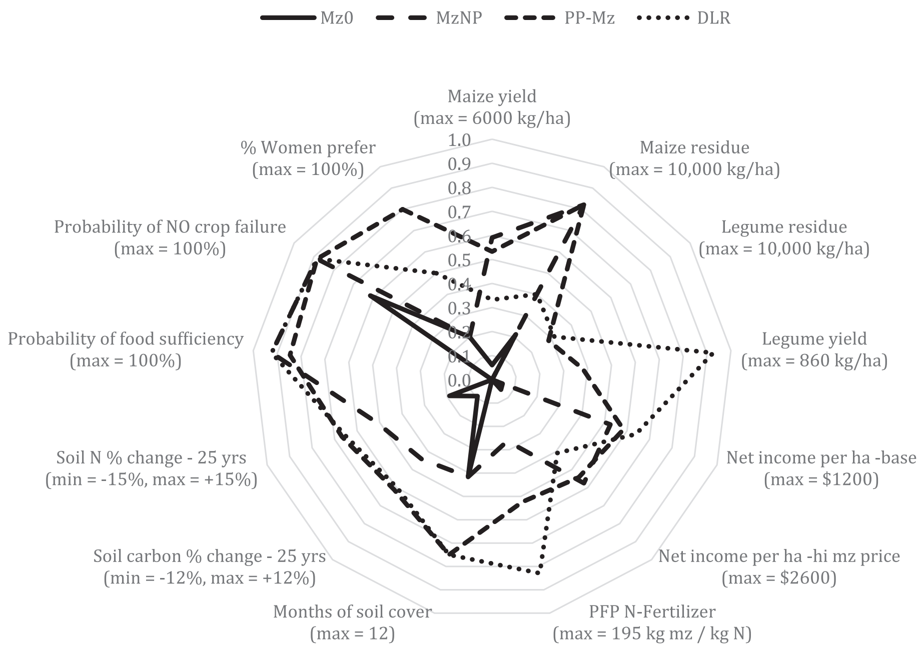

**Fig. 4.** Indicators of sustainable intensification for legume systems (pigeonpea-maize intercrop half-rate NP fertilizer = PP-Mz and doubled up legume rotation of pigeonpea-groundnut rotated with maize = DLR) and sole maize systems (unfertilized = Mz0 and full fertilizer MzNP), in Golomoti, Malawi. Crop and residue yields are reported on an annualized basis, i.e., halved for 2 year rotation DLR. Note: For specific values and details on data sources see Table 5.

half rate) and halved again in a DLR rotation (unfertilized in the DLR phase and fertilized at half rate in the maize phase of the two year system) (Table 2).

Soil accrual of N and C varied with site, as assessed from APSIM simulations. Soil organic matter gain was often modest, but some accrual was observed in Kandeu (Table 4 and Fig. 3). The PP-Mz and DLR systems generally were associated with gains in soil organic matter (or maintenance in the case of Linthipe), whereas sole maize was associated with losses in all cases.

### 3.4. Human condition

Apart from unfertilized sole maize, all technologies assessed here allowed the average household to meet 100% of calorie requirements in almost all seasons. The legume systems had the same or fewer years of crop failure than fertilized maize. Unfertilized sole maize was associated with high crop failure, particularly in the marginal Golomoti site.

### 3.5. Social

Farmer ratings from our PAR research indicated that the technologies were perceived as having similar labor requirements, with an average rating (based on a scale of 1 to 4, where 1 = low and 4 = high labor demand) of 3.33 for sole maize, 2.99 for PP-Mz intercrop and 3.20 for the DLR maize system. Female farmers at two sites, Linthipe and Golomoti, preferred PP-Mz over all other technologies. Notably, a large majority of women at Golomoti prefer the PP-Mz intercrop, presumably for direct access to the nutritious pigeonpea grain along with maize grain at this marginal site with moderate access to markets (Table 5 and Fig. 4).

## 4. Discussion

The SI indicators in five domains showed high performance overall of pigeonpea-diversified systems, compared with monoculture maize, and some important tradeoffs. Benefits included modest fertilizer requirements, soil building properties, production of nutritionally-beneficial legume grain and women farmers rated these technologies highly (with the exception of one site). In the pigeonpea diversified systems there were no major reductions in total grain yield relative to sole maize systems, nor was food security notably altered, however maize grain was sometimes reduced. Income goals were met in most cases; yet we note that this was strongly dependent on the three-way price ratio of maize grain-legume grain-fertilizer. There are few studies that take into account this dynamic economic context: the moderate grain yields of legume crops (which are biologically constrained) are often offset by high market value relative to maize grain, but not always.

Generally, the PP-Mz intercrop produced the highest net value per area, with the exception of the high maize grain price scenario where continuous, fertilized maize performed well. Production of grain legume may provide a nutritional boost and an extra source of income (Foyer et al., 2016); however the necessity to produce sufficient maize to meet family requirements is also recognized in our analysis by including annualized maize production as one of the production indicators (Droppelmann et al., 2017). At the Linthipe site fertilized sole maize was highly productive, with associated high economic returns. Similar results were observed in Kenya, where an on-farm study evaluated economic performance of legume-diversified maize systems where legume:maize price ratios were varied from 1:1 to 4:1 (Rao and Mathuva, 2000). As the price of legume grain increased relative to maize, net-present-value returns associated with a PP-Mz intercrop increased by ~20 to 80%, compared with continuous maize. A maize-DLR rotation system with a pigeonpea-cowpea intercrop, had modest returns relative to a PP-Mz intercrop, with the exception of the highest (4:1) legume:maize price ratio where DLR performed well (Rao and Mathuva, 2000). Similarly, in our study the DLR system performed as well as the PP-Mz intercrop but only at high legume grain prices (Figs. 2–4).

Many assessments of SI technologies focus on tradeoffs, and commonly find inverse relationships between productivity and environmental services (Droppelmann et al., 2017). Our assessment used the SI framework to move beyond productivity vs. environment, to consider aspects of SI such as women's ratings of technologies, and modeled food security risks. Our results are consistent with others in that diversified SI technologies did not produce the highest amount of grain yield or income (Snapp et al., 2010), but were highly associated with conservation of resources. In addition, pigeonpea diversified technologies were highly ranked by women farmers at two out of three sites, and had no out-sized risks of food insecurity (Figs. 2–4). These results are consistent with an earlier study from Northern Malawi (Bezner-Kerr et al., 2007). Altogether, we recognize that are many other aspects of human condition that were beyond the scope of this study, where we used survey data and models to explore food security risk; we recognize that much remains to be done.

Food security is challenging to assess, and we focused on risk of crop failure as a key aspect. We found few instances of pigeonpea diversified system failure in low rainfall seasons or in the dry environment of Golomoti (Fig. 4). The long duration of growth, indeterminant yield production, combined with soil cover from senesce of pigeonpea leaves (which drops leaves throughout the growing season), together these traits may contribute to environmental services and buffering of risk economically. A study of smallholder farmers located on Mt. Kenya found income was higher with crop diversification (McCord et al., 2015). By growing drought tolerant legumes, farmers may be able help ensure food security through direct consumption of protein and oil-rich harvest, as well as through sales of the legumes that support food purchases, even if maize fails (Foyer et al., 2016). In Northern Malawi where communities were supported to grow DLR crops, combined with participatory training and nutrition education, many were found to have improved child height by weight scores (Bezner Kerr et al., 2011). Taken together with our results, these are indications that pigeonpea diversification can help support sustainable trajectories of intensification. At the same time, indepth tradeoff analysis is needed to elucidate barriers, and potential costs, associated with uptake of these technologies.

### 4.1. Tradeoff analysis

The radar charts presented here illustrate that environmental conditions provide an important context for tradeoff analysis. For example, diversified systems raise concerns due to potential competition with maize, illustrated here by the high potential site – Linthipe - where maize yield was suppressed in a PP-Mz intercrop (Fig. 2). There is a maize yield penalty, although overall yield (combined maize and legume grain) is often maintained. In the marginal Golomoti site, by contrast, the tradeoff was little to nil in a PP-Mz intercrop (Fig. 4). This finding is similar to a Kenya study of paired row maize-grain legume systems: this legume diversified system was more productive and profitable compared with conventional sole maize, and this was most pronounced at a marginal site (Mucheru-Muna et al., 2010).

Our study illustrates that the large amount of maize grain produced and net income from fertilized maize may be a barrier to adoption of alternative systems. For farmers with small land holdings, this tradeoff can be steep, and fertilized maize is the most appropriate technology according to many of the metrics shown here (Fig. 2). However, there are sustainability issues with this technology, as indicated by the poor land cover and (predicted) declines in soil C (Fig. 2). More attention is needed to the adoption barrier faced by poorly-resourced households who may not be able to diversify beyond maize production without government investments, in food safety nets, and in agronomic education. For example, knowledge is key to fine-tuning SI technologies, through crop population densities and use of ratooning practices, combined with judicious use of inputs (Letourneau et al., 2011; Rogé et al., 2016).

In systems theory, a causal loop diagram is a way of representing the positive and negative linkages among complex system components, which is a critical first step in understanding system behavior and tradeoffs. In Fig. 5 we present a causal loop diagram of legume diversified systems, including direct and indirect effects across the five SI domains. Starting with increased production of groundnut and pigeonpea (through the intercrop and DLR systems), predicted improvements in soil N and C in turn could result in more stable maize yields and reduced need for fertilizer. The legumes provide more stable profits as well as nutritious food and increased security of staples via maize production. One clear tradeoff mentioned above is that of less land available for maize grain yield with the DLR system (double-lined arrow at top of Fig. 5). In developing the diagram, we were also able to identify linkages that are not currently analyzed through our research. Those data gaps are summarized next, as a focal point for future investigations.

### 4.2. Social conflict regarding residue management

A key assumption for the analysis presented in the results is that farmers will be able to utilize the legume residues to enhance soil resources (dashed box in Fig. 5). Currently many farmers burn residues, while others transport legume residues to the home with the harvest, where they may be consumed by livestock or composted (Mungai et al., 2016). More research is required to document farmer perceptions and practices around residue management but other studies in Malawi have indicated little knowledge regarding long-term negative consequences

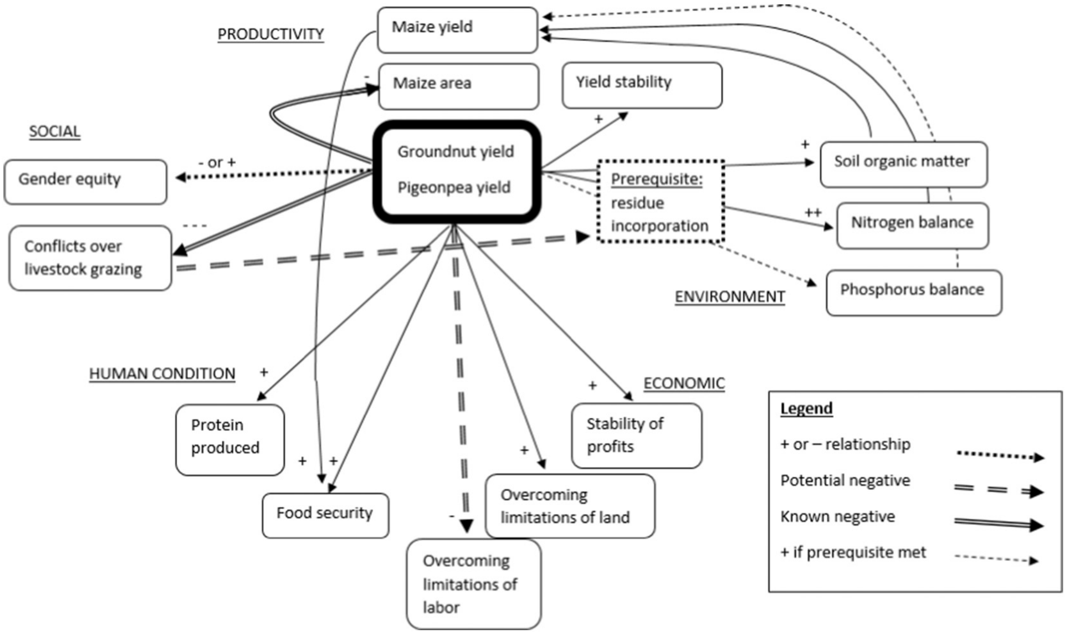

**Fig. 5.** Causal loop diagram of the direct and indirect effects driven by increased production of groundnut and pigeonpea. Notes: Black arrows show positive effects, bold arrows show negative effects and dashed arrows may be positive or negative, where tentative linkages indicate further research needs. The strength of the effect is shown by the number of + or – signs near the head of the arrow.

of burning residues, and widespread concerns about pests associated with residue incorporation practices (Snapp et al., 2002b).

Limited production of residue biomass, and complex, competing demands for this resource, is emerging as a key SI issue (Valbuena et al., 2012). Integration of crops with longer growth cycles into production systems supports intensification of crop-livestock systems in a sustainable manner, through generation of nutrient-enriched feed, extension of photosynthetic activity, and soil-root biology for enhanced nutrient access (Drinkwater and Snapp, 2008). However, there is also risk that introduction of long-lived legume crops could acerbate community conflicts among crop producers and livestock owners (double-lined arrow to the left in Fig. 5, and see Baudron et al., 2014). Studies of community and farm level resource flows in Kenya indicate a status quo that favors livestock owners who control the manure from their animals, though the residues they feed on come from the entire community (Tittonell et al., 2005). Long term soil benefits can accrue from legume production if the residues enhance animal production and the increased manure is returned to the fields (Vesteeg and Koudokpon, 1993); education on this topic has been identified as a simple and cost-effective approach to supporting climate-smart mitigation and adaptation outcomes in Tanzania livestock systems (Notenbaert et al., 2017).

The potential for crop-livestock conflict in resource use, as well as potential complementarity, has emerged within the Africa RISING project. In 2012 on-farm research trials were located close to villages and were subjected to high livestock pressure, which led to a complete loss of many pigeonpea plants, and grain as well. Many of pigeonpea's benefits are derived from its long growth period, which leaves it vulnerable to grazing once other crops are harvested (Rogé et al., 2016). Farmers who have expanded their experimentation with pigeonpea have located these new 'baby trial expansion plots' at a distance from the village. How to support innovations in community management of livestock is emerging as a key research gap, one that needs to be addressed concurrent with crop diversification to support environmentally-sound practices. Supporting this finding, crop-livestock integration with improved forages was recently identified as one of the only smallholder farming systems predicted to generate successful win-wins for mitigation and adaptation to climate change (Hammond et al., 2017).

### 4.3. Complex gender effects

There are complex gender effects related to the legume systems (dashed arrow to the left in Fig. 5). Through application of a SI indicator framework we explicitly considered women's preferences for technologies, which provided novel insights at two locations (Figs. 2 and 4). Women are primarily responsible for growing crops for nutrition in Malawi and this should be taken into consideration if human nutrition is a policy goal. Indeed, we found that women ranked PP-Mz intercrops and DLRs substantially higher than men at two of the Africa RISING sites. When a legume becomes a cash crop, literature provides precedents whereby there is a shift towards male production of the crop and control of generated cash (Njuki et al., 2011). This could have negative impacts, if women and children are worse off due to legume crop sales and reduced consumption of legume products. Malawi's groundnut exports have increased by 18% per year from 2004 to 2014 (Edelman and Aberman, 2015).

If legumes are grown for soil fertility improvement, then they may be valued by both genders. This is illustrated by a recent study in Central Malawi utilizing choice experiment methodology to explore farmer perceptions and preferences for legumes (Waldman et al., 2016). Both men and women were found to be interested in soil fertility attributes of legumes, although there were some surprising gaps in knowledge regarding which legume types and management practices build soil fertility. A survey of Central Malawi farmers found that women were twice as likely as men to be involved in experimenting with legume varieties and combinations with other SI technologies (Hockett and Richardson, 2016). This is consistent with a seminal study on the gendered nature of bean knowledge in Malawi (Ferguson, 1994).

### 4.4. Uncertain labor requirements

Another data gap involves the challenges to obtain reliable information on labor requirements for SI technologies on smallholder farms. Work is under way to have farmers rate each technology that they tested in their baby trials according to their perception of labor requirements. Initial feedback from farmers is that harvesting pigeonpea requires an extra trip to the field during a time of processing the maize harvest (dashed double-lined arrow pointing down in Fig. 5), yet overall farmer ratings of labor requirements were similar across technologies (ranged from 3 to 3.3, on scale of 1 = low to 4 = high). The challenges associated with understanding labor ratings point out that an iterative assessment of SI technologies is needed, as farmers progress from concept to testing, and from adaptation to wide scale adoption. This is illustrated by participatory research in Mali, which provides an example of how stakeholders could be engaged with to further the process of adaptation to improve labor ratings and address other locally identified priorities (Falconnier et al., 2017).

## 5. Conclusion

This analysis of options for sustainable intensification in Malawi has demonstrated the importance of assessing sustainability in a holistic manner through application of a SI indicator framework. The mixed methods approach using data from participatory on-farm trials linked to modeling showed the potential for achieving improved soil fertility while still enabling farmers to meet their immediate consumption needs and address less easily quantified traits as ascertained by farmer ratings. Although social dimensions were not studied indepth, the importance of considering female farmer ratings was illustrated as these did not always line up with profitability or productivity traits. Another important lesson was that agro-ecozone markedly affected tradeoffs around production, profits and soil impacts. Extension education may be particularly necessary in marginal environments where commercial agriculture has modest returns and improving soil quality is complex, requiring greater knowledge and a longer time horizon. Also, risk mitigation is crucial in these marginal areas, which may require government support to motivate farmers to invest in SI technologies.

Overall, the analysis of indicators for SI supported elucidation of tradeoffs and synergies as they relate to the diverse objectives of farmers, and of society more broadly. It also facilitated the identification of important research gaps. For promising SI options to be widely adopted it will be important to ascertain how to avoid or minimize conflicts with livestock owners and to better understand the complex gender effects related to legume production. It will also be important to document labor requirements of each system and adjust the technologies where possible. Taken together, this study found evidence that SI is achievable to varying degrees, if attention is paid to agroecosystem potential, and to developing policy interventions that consider the implications of subsidies that influence tradeoffs among investments in cereals, legumes and nutrient management.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.01.012.

## Funding

This work was supported by the United States Agency for International Development (USAID) under Cooperative Agreement No. AID-OAA-L-14-00006, Feed the Future Innovation Lab for Sustainable Intensification and USAID Africa RISING-Malawi (USAID No. AID-BFS-G-11-00002), led by IITA with Michigan State University (MSU), Lilongwe University of Agriculture and Natural Resources (LUANAR), International Center for Tropical Agriculture (CIAT) and Malawi DAES.

The contents are the sole responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

## Acknowledgments

The Malawi Government Ministry of Agriculture Department of Agricultural Extension Services (DAES) and smallholder farmers in Central Malawi are gratefully acknowledged as our inspiring partners.

## References

APSIM Initiative. 2013. APSoil. [http://www.apsim.info/Products/APSoil.aspx].

Baudron, F., Jaleta, M., Okitoi, O., Tegegn, A., 2014. Conservation agriculture in African mixed crop-livestock systems: expanding the niche. Agric. Ecosyst. Environ. 187, 171–182.

Baulcombe, D., Crute, I., Davies, B., Dunwell, J., Gale, M., Green, N., Jones, J., Mee, S., Pretty, J., Simpson, A., Stilgoe, J., Sutherland, W., Toulmin, C., 2009. Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture. The Royal Society, London.

Bell, S., Morse, S., 2004. Delivering sustainability therapy in a projectified world. In: Proceedings International Sustainable Development Research Conference, 2004, Manchester, UK, . http://oro.open.ac.uk/114/.

Bezner Kerr, R.B., Berti, P.R., Shumba, L., 2011. Effects of a participatory agriculture and nutrition education project on child growth in northern Malawi. Public Health Nutr. 14 (08), 1466–1472.

Bezner-Kerr, R., Snapp, S.S., Chirwa, M., Shumba, L., Msachi, R., 2007. Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil fertility. Exp. Agric. 43, 437–453.

Blackie, M., Dixon, J., 2016. Maize mixed farming systems: an engine for rural growth. In: Dixon, J., Garrity, D., Boffa, J.-M., Williams, T., Amede, T., Auricht, C., Lott, R., Mburathi, G. (Eds.), Farming Systems and Food Security in Africa: Priorities for science and policy under global change. Routledge, London and New York.

Cassman, K.G., Dobermann, A., Walters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. AMBIO 31 (2), 132–140.

Chikowo, R., Snapp, S.S., Grabowski, P., Odhong, J., Hoeschle-Zeledon, I., Bekunda, M., 2018. Farm typologies use in targeting sustainable intensification. Agron. Sustain. Dev (Ms. in press).

Chirwa, E., Dorward, A., 2013. Agricultural Input Subsidies: The Recent Malawi Experience. Oxford University Press, Oxford, UK.

Darmadi-Blackberry, I., et al., 2004. Legumes: the most important dietary predictor of survival in older people of different ethnicities. Asia Pac. J. Clin. Nutr. 13, 217–220.

Dijkshoorn, J.A., Leenaars, J.G.B., Huting, J.H.M., Kempen, B., 2016. Soil and terrain database of the Republic of Malawi. In: Report 2016/01. ISRIC—World Soil Information, Wageningen, Netherlands, http://dx.doi.org/10.17027/isric-wdcsoils.20160001.

Drinkwater, L.E., Snapp, S.S., 2008. Nutrients in agroecosystems: rethinking the management paradigm. Adv. Agron. 92, 163–186.

Droppelmann, K.J., Snapp, S.S., Waddington, S., 2017. Sustainable intensification technologies for smallholder maize-based farming systems in sub-Saharan Africa. Food Secur. 9, 133. http://dx.doi.org/10.1007/s12571-016-0636-0.

Edelman, B., Aberman, N.L., 2015. Promoting exports of low-aflatoxin groundnut from Malawi. In: MaSSP Policy Note 21. Washington D.C, International Food Policy Research Institute (IFPRI). http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129180.

Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Adam, M., Sogoba, B., Giller, K.E., 2017. Co-learning cycles to support the design of innovative farm systems in southern Mali. Eur. J. Agron. 89, 61–74.

Ferguson, A., 1994. Gendered science: a critique of agricultural development. Am. Anthropol. 96, 540–552.

Foyer, C.H., Lam, H.M., Nguyen, H.T., Siddique, K.H., Varshney, R.K., Colmer, T.D., Cowling, W., Bramley, H., Mori, T.A., Hodgson, J.M., Cooper, J.W., 2016. Neglecting legumes has compromised human health and sustainable food production. Nature Plants 2, 16112.

Godfray, H.C.J., 2015. The debate over sustainable intensification. Food Secur. 7, 199–208. http://dx.doi.org/10.1007/s12571-015-0424-2.

Gunton, R.M., Firbank, L.G., Inman, A., Winter, D.M., 2016. How scalable is sustainable intensification? Nat. Plants. 2, 1–4. http://dx.doi.org/10.1038/NPLANTS.2016.65.

Hammond, J., Fraval, S., van Etten, J., Suchini, J.G., Mercado, L., Pagella, T., Frelat, R., Lannerstad, M., Douxchamps, S., Teufel, N., Valbuena, D., van Wijk, M.T., 2017. The rural household multi-indicator survey (RHoMIS) for rapid characterisation of households to inform climate smart agriculture interventions: description and applications in East Africa and central America. Agric. Syst. 151, 225–233.

Hockett, M., Richardson, R.B., 2016. Examining the drivers of agricultural experimentation among smallholder farmers in Malawi. Exp. Agric. 1–21. http://dx.doi.org/10.1017/S0014479716000673.

Holzworth, D.P., Huth, N.I., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., 2014. APSIM–evolution towards a new generation of agricultural systems simulation. Environ. Model Softw. 62, 327–350.

Jayne, T.S., Chamberlin, J., Headey, D.D., 2014. Land pressures, the evolution of farming systems and development strategies in Africa: a synthesis. Food Policy 48, 1–17.

Johnson, N., Lilja, N., Ashby, J.A., 2003. Measuring the impact of user participation in agricultural and natural resource management research. Agric. Syst. 78, 287–306.

Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., Mejía, J.L., 2011. Does plant diversity benefit agroecosystems? A synthetic review. Ecol. Appl. 21 (1), 9–21.

Li, G., Messina, J.P., Peter, B.G., Snapp, S., 2017. Mapping land suitability for agriculture in Malawi. Land Degrad. Dev. http://dx.doi.org/10.1002/ldr.2723.

Loos, J., Abson, D.J., Chappell, M.J., Hanspach, J., Mikulcak, F., Tichit, M., Fischer, J., 2014. Putting meaning back into "sustainable intensification". Front. Ecol. Environ. 12, 356–361. http://dx.doi.org/10.1890/130157.

McCord, P.F., Cox, M., Schmitt-Harsh, M., Evans, T., 2015. Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya. Land Use Policy 42, 738–750.

Messina, J.P., Peter, B.G., Snapp, S.S., 2017. The myth of the Malawian farm input subsidy program. Nat. Plants 3. http://dx.doi.org/10.1038/nplants.2017.13.

Mhango, W., Snapp, S.S., Kanyama-Phiri, G.Y., 2013. Opportunities and constraints to legume diversification for sustainable cereal production on African smallholder farms. Renew. Agric. Food Syst. 28, 234–244.

Ministry of Agriculture and Food Security (MAFS), 2012. Malawi Guide to Agriculture. Published by Agricultural Communication Branch. Government of Malawi, Lilongwe, Malawi.

Mucheru-Muna, M., Pypers, P., Mugendi, D., Kung'u, J., Mugwe, J., Merckx, R., Vanlauwe, B., 2010. A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. Field Crop Res. 115 (2), 132–139.

Mungai, L.M., Snapp, S., Messina, J.P., Chikowo, R., Smith, A., Anders, E., Richardson, R.B., Li, G., 2016. Smallholder farms and the potential for sustainable intensification. Front. Plant Sci. 7. http://dx.doi.org/10.3389/fpls.2016.01720.

Njuki, J., Kaaria, S., Chamunorwa, A., Chiuri, W., 2011. Linking smallholder farmers to markets, gender and intra-household dynamics: does the choice of commodity matter? Eur. J. Dev. Res. 23, 426–443.

Notenbaert, A., Pfeifer, C., Silvestri, S., Herrero, M., 2017. Targeting, out-scaling and prioritising climate-smart interventions in agricultural systems: lessons from applying a generic framework to the livestock sector in sub-Saharan Africa. Agric. Syst. 151, 153–162.

Ollenburger, M., Snapp, S.S., 2014. Model applications for sustainable intensification of African water-limited cropping systems in a changing world. Adv. in Model 5, 375–398.

Orr, A., Kambombo, B., Roth, C., Harris, D., Doyle, V., 2015. Adoption of integrated food-energy systems: improved cookstoves and pigeonpea in southern Malawi. Exp. Agric. 51, 191–209.

Peter, B., Messina, J.P., Frake, A.N., Snapp, S.S., 2017. Scaling Agricultural Innovations: Pigeonpea in Malawi. The Professional Geographer, Ms (in press).

Petersen, B., Snapp, S.S., 2015. What is sustainable intensification: views from experts. Land Use Policy 46, 1–10. http://dx.doi.org/10.1016/j.landusepol.2015.02.002.

Pretty, J., Toulmin, C., Williams, S., S., 2011. Sustainable intensification in Africa agriculture. Int. J. Agric. Sustain. 9, 5–24.

Rao, M.R., Mathuva, M.N., 2000. Legumes for improving maize yields and income in semi-arid Kenya. Agric. Ecosyst. Environ. 78 (2), 123–137.

Robertson, G.P., Vitousek, P.M., 2009. Nitrogen in agriculture: balancing the cost of an essential resource. Annu. Rev. Environ. Resour. 34, 97–125.

Robertson, M.J., Sakala, W., Benson, T., Shamudzarira, Z., 2005. Simulating response of maize to previous velvet bean (Mucuna pruriens) crop and nitrogen fertilizer in Malawi. Field Crop Res. 91, 91–105.

Rogé, P., Snapp, S.S., Kakwera, M.K., Mungai, L., Jambo, I., Peter, B., 2016. Ratooning and perennial staple crops in Malawi: a review. Agron. for. Sustain. Dev. 36, 50. http://dx.doi.org/10.1007/s13593-016-0384-8.

Smith, A., Snapp, S., Dimes, J., Gwenambira, C., Chikowo, R., 2016. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agric. Syst. 145, 139–149.

Smith, A., Snapp, S.S., Chikowo, R., Thorne, P., Bekunda, M., Glover, J., 2017. Measuring sustainable intensification in smallholder agroecosystems: a review. Glob. Food Secur. 12, 127–138.

Snapp, S.S., 1998. Soil nutrient status of smallholder farms in Malawi. Commun. Soil Sci. Plant Anal. 29, 2571–2588.

Snapp, S.S., Kanyama-Phiri, G.Y., Kamanga, B., Gilbert, R., Wellard, K., 2002a. Farmer and researcher partnerships in Malawi: developing soil fertility technologies for the near-term and far-term. Exp. Agric. 38, 411–431.

Snapp, S.S., Rohrbach, D.D., Simtowe, F., Freeman, H.A., 2002b. Sustainable soil management options for Malawi: can smallholder farmers grow more legumes? Agric. Ecosyst. Environ. 91, 159–174.

Snapp, S.S., Jones, R.B., Minja, E.M., Rusike, J., Silim, S.N., 2003. Pigeon pea for Africa: a versatile vegetable - and more. Hortscience 38, 1073–1078.

Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can support a greener revolution in Africa. Proc. Natl. Acad. Sci. 107, 20840–20845.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agric. Ecosyst. Environ. 110, 149–165.

Tropical Rainfall Measuring Mission Project (TRMM), 2016. TRMM Product 3b43, NASA/JAXA. Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC). http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B43_readme.shtml, Accessed date: 23 November 2016.

Valbuena, D., Erenstein, O., Tui, S.H.K., Abdoulaye, T., Claessens, L., Duncan, A.J., Gerard, B., Rufino, M.C., Teufel, N., van Rooyen, A., van Wijk, M.T., 2012.

Conservation agriculture in mixed crop-livestock systems: scoping crop residues trade-offs in Sub-Saharan Africa and South Asia. Field Crop Res. 132, 175–184.

Van Vugt, D., Franke, A.C., Giller, K.E., 2016. Participatory research to close the soybean yield gap on smallholder farms in Malawi. Exp. Agric. 1–20. http://dx.doi.org/10.1017/S0014479716000430.

Vesteeg, M.N., Koudokpon, V., 1993. Participative farmer testing of four low external input technologies to address soil fertility decline in mono province (Benin). Agric. Syst. 42, 266–276.

Waldman, K.B., Ortega, D.L., Richardson, R.B., Clay, D., Snapp, S.S., 2016. Preferences for legume attributes in maize-legume system cropping systems in Malawi. Food Secur. 8, 1087. http://dx.doi.org/10.1007/s12571-016-0616-4.