Sustainable intensification options for smallholder maze-based farming systems in sub-Saharan Africa

Klaus J. Droppelmann, Sieglinde. S. Snapp & Stephen R. Waddington (2017)

Correct citation:

Droppelmann, K.J.; Snapp, S.S.; and Waddington, S.R. (2017). Sustainable intensification options for smallholder maze-based farming systems in sub-Saharan Africa. In Food Security (2017) 9:133-150, DOI 10.1007/s12571-016-0636-0

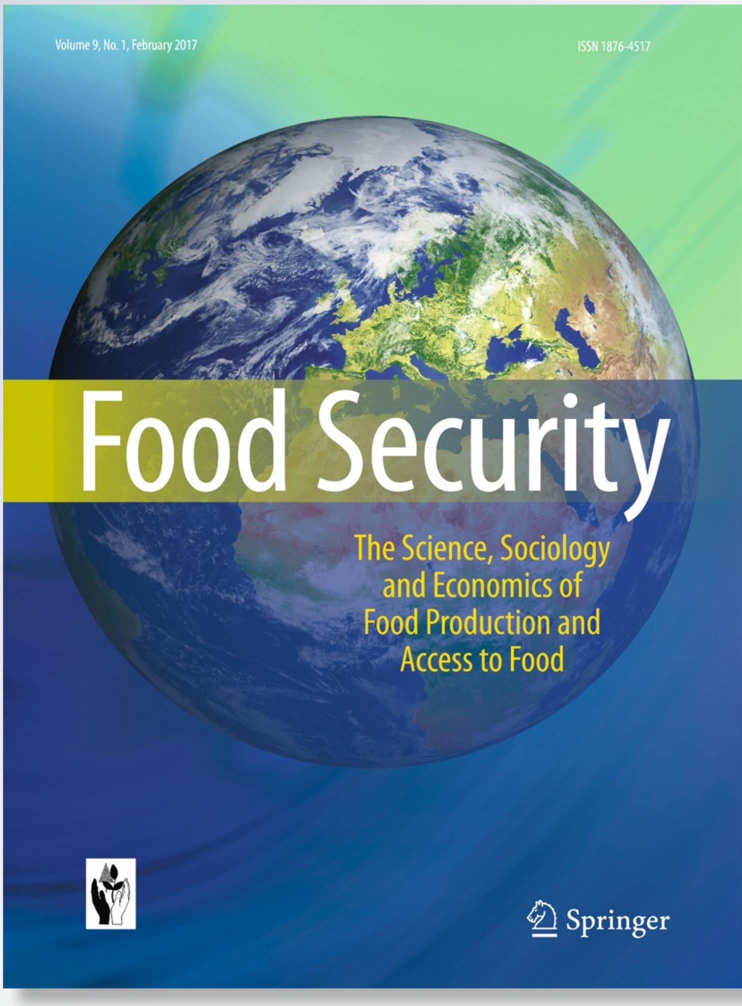
Sustainable intensification options for smallholder maize-based farming systems in sub-Saharan Africa

Klaus J. Droppelmann, Sieglinde S. Snapp & Stephen R. Waddington

Food Security
The Science, Sociology and Economics of Food Production and Access to Food

ISSN 1876-4517
Volume 9
Number 1

Food Sec. (2017) 9:133-150
DOI 10.1007/s12571-016-0636-0



Springer

Food Sec. (2017) 9:133–150
DOI 10.1007/s12571-016-0636-0

ORIGINAL PAPER

Sustainable intensification options for smallholder maize-based farming systems in sub-Saharan Africa

Klaus J. Droppelmann[1] · Sieglinde S. Snapp[2] · Stephen R. Waddington[3]

Received: 5 March 2016 / Accepted: 4 December 2016 / Published online: 11 January 2017

Abstract Appropriate sustainable intensification (SI) of agriculture is required in Sub-Saharan Africa to meet the rising demand for food and protect resources. Agroforestry and green manures, diversification with grain legumes, conservation agriculture and integrated nutrient management with mineral and organic fertilizers are SI options widely promoted for maize-based African smallholder systems. To assess the potential of SI options to contribute to multiple ecosystem services in these systems, we evaluated 17 published multi-year and site studies, using radar charts to systematically measure provisioning services (annualized maize grain and protein yields) and supporting services (vegetative biomass, rain productivity and agronomic efficiency of N fertilizer) among the studies and across technologies. We frequently observed trade-offs amongst provisioning and supporting ecosystem services, especially in rotational systems where the addition of a grain legume increased maize response to fertilizer but reduced annualized maize grain yields. Consistent gains in maize grain yield and vegetative biomass, and protein yield and rain productivity were obtained with the application of N fertilizer across the studies. More efficient use of N fertilizer was associated with legume diversification, particularly intercrop systems, with large incremental yield gains (30–80 kg grain kg^{-1} N fertilizer) at low fertilizer rates (< 50 kg N ha^{-1}). These systems produced substantial amounts of grain, protein, vegetative biomass and high resource use efficiency (1 to 5-fold increase relative to sole maize). In contrast, performance was inconsistent from conservation tillage practices. The highly variable performance of many options that contribute to SI suggests the importance of their adaptation to local conditions and support for farmer innovation, rather than prescribing the use of fixed SI interventions. Overall, for maize system intensification, we suggest expanding farmer access to multipurpose legumes (such as long-duration pigeon pea) that provide food and copious biomass, and to N fertilizer, along with the local adaptation of water-conserving tillage practices.

Keywords Ecosystem services · Sustainable agriculture · Crop diversification · Grain legume · Green manure · Agroforestry · Mineral fertilizer · Conservation tillage

✉ Klaus J. Droppelmann
klaus.droppelmann@picoteam.org

Sieglinde S. Snapp
snapp@msu.edu

Stephen R. Waddington
srwaddington@gmail.com

[1] PICOTEAM, 8 Leda Street, Kensington, Johannesburg 2094, South Africa

[2] Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI 48824, USA

[3] Apartado Postal 4-205, Colonia Chapultepec, CP62451 Cuernavaca, Morelos, Mexico

Introduction

Research on agricultural productivity is grappling with the growing global demand for food (Beddington 2010; Godfray 2015). Attention has shifted from extensive agricultural systems, based on the assumption of abundant land and resources, to the efficient and sustainable management of finite land, nutrients and soil fertility, water and energy resources (Boserup 1965; Cassman 1999; Fischer et al. 2005; Keating et al. 2010; Vanlauwe et al. 2011). In sub-Saharan Africa (SSA), the regeneration of soil resources historically involved long-term natural bush fallows between mixed cropping phases, but this practice has disappeared in most areas as it required abundant land resources (Kumwenda et al. 1996; Vissoh et al. 1998). Commonly, smallholder farms have fields that have been continuously cropped for many decades and the decline in soil fertility has been well recognized as a widespread and severe constraint to crop production (e.g. Sanchez 2002; Okalebo et al. 2006). There is also substantial concern about the effects of an increasingly variable climate, which will severely disrupt farming in many parts of SSA (Funk et al. 2008; Pauw et al. 2011). At the policy level, the Comprehensive Africa Agriculture Development Program (CAADP) agenda of the African Union aims at ensuring food security and economic growth through agricultural intensification, and places emphasis on protection of the natural resource base through the judicious application of sustainable land and water management practices (Bwalya et al. 2009).

Intensification of agriculture is underway in some sectors and regions in SSA, often promoted through government-subsidized access to mineral fertilizers and improved seeds, and the development of markets for farm inputs and products. To help sustain financial investments in agricultural subsidies, both governments and farmers need to ensure such programs provide high returns (Dorward and Chirwa 2011). However, a narrow focus on chemical inputs alone for maize in many of these initiatives raises concerns about negative environmental impacts, and questions about sustainability. Long-term field crop experiments in Kenya (Nandwa and Bekunda 1998) and Zimbabwe (Waddington et al. 2007a and b) have clearly shown declining yield trends for mineral fertilizer-intensive treatments in a maize monocrop system.

Sustainable intensification

Sustainable intensification (SI) has been widely promoted in recent years as a way to simultaneously address the need for more food and for environmental security (Pretty et al. 2011; Pretty and Bharucha 2014; Godfray 2015; Chartres and Noble 2015). SI is broadly defined as the investment of inputs and capital to increase crop productivity over the long-term, while protecting the underlying resource base (Matson et al. 1997; Pretty et al. 2011). Several authors, including Pretty and Bharucha (2014) and Giller et al. (2015), have emphasized the need to better identify technologies that are appropriate for the sustainable intensification of smallholder agriculture in SSA. Such interventions have to address the most severe production constraints (i.e. the major contributors to yield gaps) with smallholder maize production in SSA, which include problems with N inputs and their management and with the management of water resources (Waddington et al. 2010). In addition, by raising ecosystem services and productivity per unit land area, SI may spare marginal lands from being brought into agriculture.

Progress has been made to understand the performance of SI inputs and practices on African smallholder farms over the last 20 years, especially those related to soil fertility, although the adoption of many of these technologies has remained somewhat elusive and patchy (Snapp 1998; Waddington et al. 2004; Ajayi et al. 2007). Practices associated with SI include integrated nutrient management with various forms of organic matter inputs and mineral fertilizers (which have been reviewed for southern Africa by Snapp et al. (1998) and Mafongoya et al. (2006); in east Africa by Okalebo et al. (2006); and for west Africa see Schlecht et al. (2006)), and resource conserving technologies included in conservation agriculture (CA) (e.g. Pretty et al. 2011). Kassam et al. (2009) outlined the contributions from CA to enhancing the provision of ecosystem services.

Interest in SI continues to grow, and in the last decade there have been various comprehensive, multi-site and multi-year studies that have rigorously assessed the performance of SI interventions on smallholder farms and field research stations in SSA. This literature deserves a close look to develop an evidence-based understanding of contributions to food production in conjunction with ecosystem service provision over a range of environmental conditions.

Ecosystem services

Agro-ecosystems generate provisioning services (including food, fodder, fuel and fibre) and provide supporting, regulating and cultural ecosystem services, such as carbon sequestration, nutrient cycling, pest regulation, water retention / purification, and biodiversity (Shennan 2008; Newton et al. 2009). However, agricultural activity may also result in ecosystem disservices that include the loss of biodiversity, nutrient runoff / leakage, and the emission of greenhouse gases (Power 2010; Reynolds et al. 2015). Consequently, additional to increased crop productivity, SI technologies need to demonstrate improved input use efficiencies and minimal environmental impacts through the conservation of resources and maintenance of soil productivity (Vanlauwe et al. 2011). A review of SI field experiments that have been conducted in SSA over multiple years and sites provides an opportunity to evaluate their performance in contributing to ecosystem services. One way to gauge performance is to assess variables that correlate with environmental services in conjunction with provisioning services (Daily and Matson 2008; Power 2010).

SI technologies

Many types of production inputs and management practices can potentially contribute to pathways to the sustainable intensification of Africa's maize-based systems. Their relative suitability and contribution will vary enormously depending on local biophysical and socio-economic circumstances. For simplicity, in our assessment we call such interventions 'SI technologies'. Three major categories of SI technology widely used in maize-based farming systems in SSA are green manures/agroforestry interventions, diversification with grain legumes, and conservation agriculture (CA)/conservation tillage (CT). We included both perennial agroforestry species and annual viney and shrubby legumes as 'green manure' technologies (e.g. Garrity et al. 2010; Ajayi et al. 2011). Diversification of maize with annual grain legumes was assessed as an important smallholder cropping system that provides human food, products for market sales and benefits soil fertility (Giller 2001; Snapp et al. 2002a; Mafongoya et al. 2006). The shortage of nitrogen (N) is a key factor that limits productivity of smallholder maize-based systems across SSA (Sanchez 2002; Morris et al. 2007), and legumes address this challenge in a sustainable manner through the biological fixation of N that builds soil organic matter (SOM) and soil N (Drinkwater et al. 1998; Gregorich et al. 2001). The suppression of weeds, the breaking of pest cycles and biophysical rehabilitation of soil by deep taproot systems have also been demonstrated through the integration of legumes (Chikowo et al. 2003).

Conservation agriculture (CA) incorporates the principles of minimal soil disturbance and retention of crop cover on the soil surface along with diversification of crops in the system (Hobbs et al. 2008). CA has been widely advocated and promoted in SSA for several decades (e.g. Fowler and Rockstrom 2001; Kassam et al. 2009) and critically discussed (Giller et al. 2009; Brouder and Gomez-Macpherson 2014). In our assessment, we focused on the conservation tillage (CT) aspects of CA, since this has been the subject of several long-term, multiple site on-farm studies.

Across these three broad categories of SI intervention, applications of N fertilizer play an important role to enhance the productivity of maize cropping. Due to this cross-cutting nature we decided to examine the efficiency of N-fertilizer applications, where possible, for every treatment within each study instead of placing it in a separate category.

When reviewing the recent literature we observed that there has been little attention paid to the systematic assessment of practices that may lead to the sustainable intensification of smallholder maize-based farming in SSA by maintaining the provision of ecosystem services and food security. Thus the objective of this case study was to evaluate field-based evidence on provisioning and supporting ecosystem services associated with a range of green manure/agroforestry, legume diversification and CT studies that were conducted at SSA farm sites. The assessment covers smallholder maize-based cropping systems from semi-arid to sub-humid tropical SSA. These are among the most important rainfed farming systems in the region (Dixon et al. 2001), and are responsive to SI fertility inputs. In contrast, the mixed tuber-tree systems typical of high rainfall areas generally show moderate yield response to inputs and were hence not considered.

Methods

To evaluate their maize grain yield and protein yield benefits to African small-scale farmers, we compiled information from 17 maize-based studies on the performance of farming practices aimed at SI over a range of agro-ecological conditions. We chose studies that provided a combination of information on the 'ecosystem' services attributes identified and conducted over several or more years, preferably at multiple sites. We first examined around 50 candidate studies published in peer-reviewed research journals (12 on agroforestry/green manures, 13 on legume diversification and 20 on conservation tillage) obtained through systematic searches of the Scopus database, from which the 17 were selected for close assessment in this study.

The selected studies reported on maize grain yield, maize stover yield, aboveground biomass, seasonal rainfall, N fertilizer application rate, and (in most cases) employed an unfertilized control treatment. For systems diversified with legumes, we included papers that reported legume biomass or dry matter production. In our analysis, we present a graphical comparison of the provisioning and supporting services using radar charts. These allowed us to assess synergies and trade-offs among services that help identify suitable SI technologies, point to further research needs and inform policy making processes.

We distinguish between provisioning services that directly benefit farmers through harvested materials (i.e. maize grain and protein yields) and supporting ecosystem services, such as soil fertility, water holding capacity, resistance to soil erosion, and carbon (C)-sequestration. Since it is not possible to *post-hoc* measure many of these factors in the selected studies, we employed proxies that were measured to gauge the potential of the farming practice in question to contribute to supporting services. We assessed incremental maize grain yield gain per unit of N-fertilizer, total biomass production in relation to rainfall, and production of vegetative biomass. Soil quality and C status are important indicators of sustainability, but these are often unavailable and there are methodological challenges to compare these properties across studies and over time. Thus we included the alternative measurements of agronomic efficiency of N fertilizer and biomass production per unit rainfall (Snapp et al. 2010). Biomass, a measure of aboveground net primary productivity, provides a proxy for belowground net primary productivity, which is rarely measured. The amount and quality of biomass retained on the field as soil cover or when returned to the field as animal manure plays an important role in the ability of agricultural soils to sequester C and to regenerate their inherent fertility. Furthermore, N fertilizer agronomic efficiency (NAE) and overall biomass yield per unit rainfall are indicators of resource utilization within the production system.

Explanation of variables

Maize Grain Yield is a key component of food security in smallholder maize-based farming systems. The units used were maize grain [kg ha^{-1}] harvested, annualized for rotation systems. ***An increase per unit area of land indicated intensification***.

Protein is important for dietary diversity (i.e. a balanced diet with sufficient protein consumption) and contributes to nutrition security. Dietary diversity is of increasing importance amongst development practitioners (Smith et al. 2006). Units used were protein [kg ha^{-1}] harvested from cereal and legume grain crops (annualized for rotation systems). ***An increase per unit area of land indicated intensification.***

Vegetative Biomass is important in maintaining or restoring soil fertility through an increase in soil organic C (Sanchez 2002; Giller et al. 2009) and is thus at the foundation of environmental sustainability. Although belowground biomass plays a more direct role and would be preferred as an indicator, too little data can be found in the literature to allow comparison. Units used were aboveground biomass [kg ha^{-1}] of all crops grown in the system (annualized for rotation systems) after subtracting out any biomass that is removed from the field at harvest (usually in the form of grain), giving the vegetative biomass which is available to be retained in the field as green manure/mulch and/or returned to the field in the form of animal manure. ***An increase indicates sustainability.*** In our analysis we only considered quantity, which is related to soil cover, water infiltration and storage, as well as accrual of SOM. Data was limited on quality of residues (C/N ratio), precluding our including it in the radar chart analysis: however, it is an important property (Palm et al. 2001) and we discuss residue quality for studies that reported it. Quantity of residues retained in the field also influences suppression of weeds and prevention of nutrient losses. However, competing uses for finite residue material often prevents farmers from applying mulch (Giller et al. 2009). Hence, we examined system production of vegetative biomass as a means to support the multiple demands on smallholder farms, including animal fodder, fuel and for construction.

Nitrogen Agronomic Efficiency (NAE) measures the ability of a production system to turn N fertilizer inputs into yield outcomes (Vanlauwe et al. 2011) and thus ***an increase indicates sustainable intensification.*** We used the units of grain yield for fertilized maize (treatment) minus grain yield of unfertilized maize (control) [kg ha^{-1}] over N fertilizer application to maize [kg ha^{-1}]. This metric adjusts for soil N supplied by SOM at the site by subtracting out the grain yield produced in unfertilized maize; the remaining grain is presumed to be directly related to the N fertilizer input. Since mineral fertilizer application rates are very low in SSA (Morris et al. 2007), and fertilizer is usually applied directly to maize as the main crop in a smallholder setting, we focused our analysis on maize yield return to N-application even though other crops may be present. If, for example, phosphorus (P) fertilizer inputs were applied to treatments then the metric used treatments with comparable P fertilizer levels to calculate the NAE.

Rainfall Productivity (RP) measures the ability of a production system to perform under prevailing rainfall amounts and patterns. We use the term rain productivity to distinguish it from rain use efficiency, which commonly measures the production of grain yield over rainfall (Thierfelder and Wall 2009), and to emphasize total biomass produced from rainfall. According to Stroosnijder (2007) only 5–15% of precipitation across SSA is used for transpiration by plants. Hence, farming practices that are geared towards increasing biomass production through greater use of rainfall are desirable. The units we used were total aboveground biomass (grain plus vegetative biomass, or biomass alone for green manures) of all crops grown in the production system over annual (or seasonal if applicable) rainfall [kg mm^{-1}]. ***An increase indicates sustainable intensification.*** This variable provides an indication of the ability of the soil to efficiently absorb rainfall (i.e. minimize runoff) and effectively store water in the soil profile (i.e. increase the proportion of plant available water from annual rainfall). This measure of net primary productivity potential of a treatment relative to rainfall at a given site-year is a metric of system resilience and sustainability, as performance is assessed across a gradient of rainfall-scarce environments and mesic environments, where high RP should broadly reflect the ability of a system to translate rainfall into productivity over time and space. Due to the effects of climate change, the occurrence of dry spells and flooding events is likely to increase across parts of SSA (Pauw et al. 2011). Hence, production systems that are able to utilize more water resources from annual rainfall for plant transpiration are needed.

Radar charts

Radar charts were used to visualize multiple variables in one figure to allow easy comparison of services produced by different SI technologies. Commonly, radar charts have been used with relative value axes; for example, marking the performance of each indicator relative to a prescribed optimum where all of the axes have a 0–100% scale (Smith et al. 2011). For visual representation of ecosystem services, however, we preferred absolute value axes for more accurate comparisons and to avoid masking important effects when comparing sites with different production potential. Where possible, we compared an unfertilized conventional practice in the study area (solid black line) with a fertilized one (solid grey line) and various SI technologies, both unfertilized (broken black lines and –N, indicating no mineral N fertilizer was applied) and fertilized (broken grey lines and +N, with the figure indicating the amount of N applied). If more treatments were assessed in the study we selected treatments that allow for the most meaningful comparison within and across studies. In the top right corner of each chart, key information indicating the agro-ecological conditions of the study is provided.

Calculations and assumptions

We used data extracted from the published papers or provided by the authors in absolute value form. If data were reported only in graphs, we obtained values which were as precise as possible using ocular estimation. For maize and legume grain yields, no missing data were allowed (studies were excluded if both were not reported). Protein yields were calculated using protein content values found in literature relevant to the studied agro ecologies (Snapp et al. 2010; Gilbert 2004): maize 100 g protein kg^{-1}, groundnut 210 g protein kg^{-1}, soybean 350 g protein kg^{-1}, pigeon pea 200 g protein kg^{-1}, and mucuna 310 g protein kg^{-1}. In cases where maize vegetative aboveground biomass or total aboveground biomass was not reported, we calculated these based on the reported maize grain yield using an estimated harvest index of 0.5 which is broadly suited to smallholder maize (Kihara et al. 2011). This procedure was applied to data reported in Fofana et al. (2004), Waddington et al. (2007b), Munodawafa and Zhou (2008) and Nyagumbo and Bationo (2011). For legume vegetative biomass, only reported values were used in the analysis. In cases where no unfertilized control treatment was included in the study, we used the long-term average maize grain yield for smallholders in Zimbabwe of 803 kg ha^{-1} as reported in Nyagumbo and Bationo (2011). This procedure was applied to data reported in Munodawafa and Zhou (2008), Thierfelder and Wall (2012) and Thierfelder et al. (2013a).

Results

Green manures/agroforestry

Adjei-Nsiah et al. (2007) tested several green manure and rotational cropping systems over three seasons in Ghana: continuous maize, pigeon pea or mucuna green manure rotations with maize, and a cowpea grain legume rotation with maize (Fig. 1a). All systems were followed by a maize crop in the fourth season, which received an application of 60 kg ha^{-1} of N or no N, to allow testing of N agronomic efficiency (NAE).

Maize following the green manuring rotations with pigeon pea or mucuna produced more grain than the rotation with cowpea and sole maize stands, with and without N. Benefits of the multipurpose pigeon pea and mucuna species included the production of large amounts of biomass and associated N-fixation. However, as shown in Fig. 1a, when looking at production over the four seasons together, the pigeon pea system produced an average of only 725 kg ha^{-1} of maize grain per season, whereas the other treatments with maize grown every second season or continuously ranged from 1175 to 1550 kg ha^{-1} grain per season. The grain-legume maize-cowpea rotation produced 16 to 41% more protein than any other treatment. Vegetative biomass was highest in the green manure systems and the high-quality (low C/N ratio) of biomass produced translated into positive N-balances for these treatments as reported by Adjei-Nsiah et al. (2007). However, participating farmers indicated that the high labor requirement associated with management of crop residues, especially for mucuna, curbed their acceptance of green manure technologies (Adjei-Nsiah et al. 2007).

Chikowo et al. (2004) conducted a two-year experiment on highly depleted soils in Zimbabwe over variable rainfall conditions (Fig. 1b). Season one received 1120 mm rainfall while season two received just 412 mm. Sole maize was either unfertilized (−N) or received 90 kg ha^{-1} of N in the first season and 40 kg ha^{-1} of N in the second (+90/40 N). In the rotations, soybean received 12 kg ha^{-1} of N in the first season and maize 40 kg ha^{-1} of N (+12/40 N) in the second season. Mucuna was unfertilized in the first season and maize received 40 kg ha^{-1} of N in the following season (+0/40 N). In the absence of mineral fertilizer, maize produced very little grain or vegetative biomass, highlighting the degraded state of the environment. Similar to the results from Ghana, protein yield was substantially increased in the soybean grain legume rotation with maize, while large amounts of vegetative biomass were produced in the green manure system of mucuna rotated with maize. Response to N-fertilization ranged from 13 kg of maize grain per kg N applied for the soybean maize rotation to 22 kg for sole maize. The rotation of mucuna with maize produced 18 kg of maize grain per kg N applied.

Fofana et al. (2004) studied the effect of mucuna green manure and N fertilizer on the performance of maize grown on a degraded soil in southern Togo (Fig. 1c). A mucuna-maize relay cropping system with 50 kg N ha^{-1} fertilizer applied performed best of all systems tested. Maize grain yields were improved by N fertilizer, and by relay cropping with a green manure. In addition, substantial amounts of vegetative biomass produced by mucuna were available to help rehabilitate the degraded sites. The authors also reported that the use of P fertilizer increased the recovery of N by maize after mucuna, but not without mucuna.

Beedy et al. (2010) and Akinnifesi et al. (2006, 2007) reported on various aspects and components of the same long-term agroforestry experiment at Makoka in Malawi (Fig. 1d). Akinnifesi et al. (2007) focused on the interaction and additive effects of the combined use of mineral N and P fertilizers, and organic inputs from Gliricidia intercropping on maize yield and its yield components. Data on maize stover were taken from Beedy et al. (2010) while data on maize grain yields and biomass production of Gliricidia was reported in Akinnifesi et al. (2006). Figure 1d shows that when intercropped with Gliricidia, the grain yield of maize increased by more than 50%, and NAE rose markedly. However, the largest effect was the vegetative biomass from Gliricidia leaves, which increased the vegetative biomass to almost 13 t ha^{-1}.

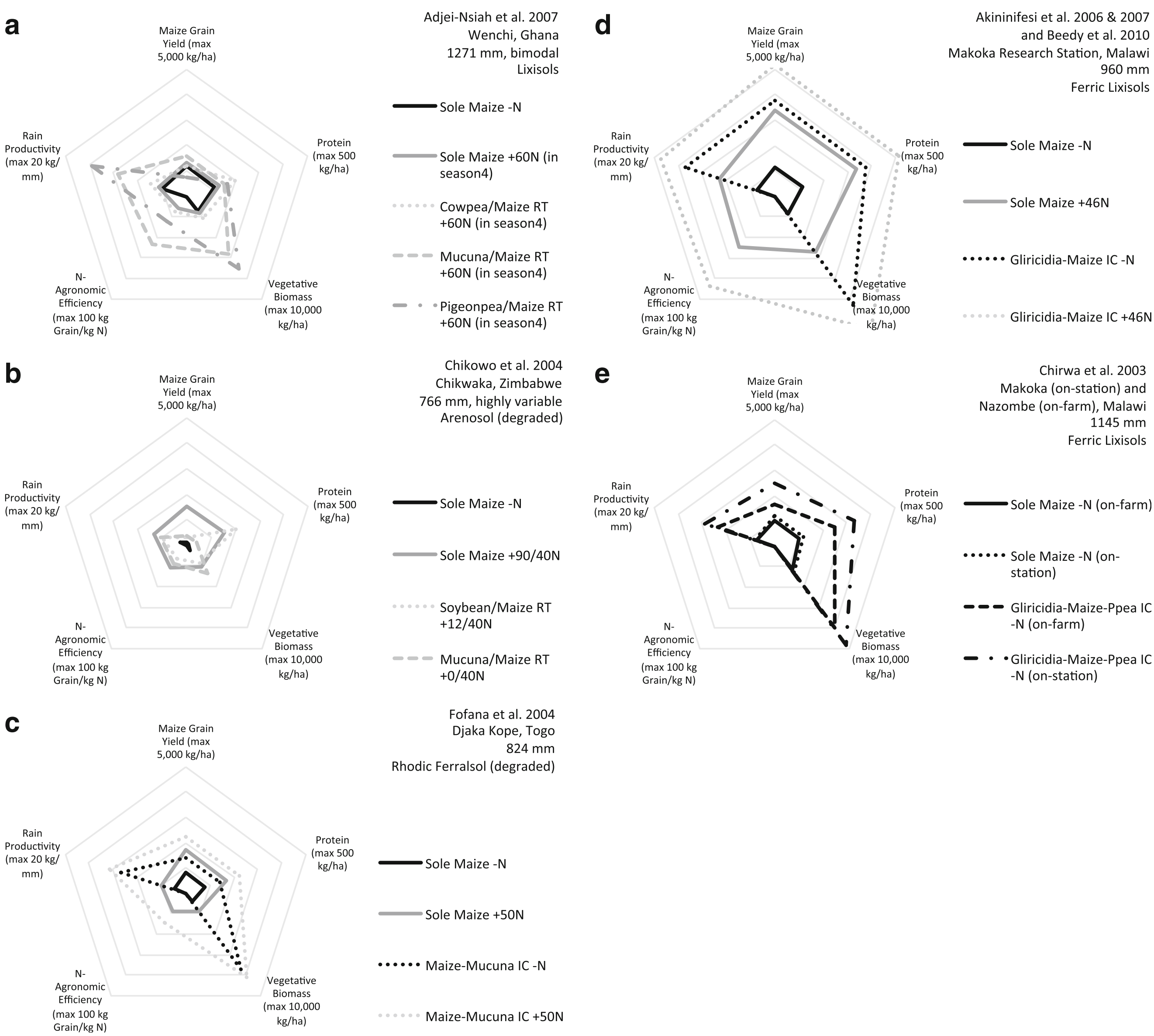


Fig. 1 Ecosystem provisioning and supporting services associated with green manuring and agroforestry, reported in seven studies conducted across sub-Saharan Africa. **a** To evaluate maize performance in rotation (RT) with green manure and grain legumes, a researcher-managed on-farm experiment was conducted on well-drained sandy loam soils over four seasons in a sub-humid, bimodal rainfall region of Ghana (Adjei-Nsiah et al. 2007). **b** Maize performance in rotation (RT) with green manure and grain legumes was assessed over two years at an on-farm site with well drained, sandy soils in a semi-arid, unimodal rainfall region of Zimbabwe (Chikowo et al. 2004). **c** Performance of maize intercropped with a green manure legume on a low-fertility, sandy clay soil in a sub-humid bimodal region of southern Togo (Fofana et al. 2004). The experiment was conducted at one on-farm site over two years; i.e. a total four seasons with maize as main crop in the long season followed by a relay crop or fallow in the short season. **d** Maize intercropped with gliricidia leguminous trees was assessed in a long-term (10 year) agroforestry field experiment at Makoka Research Station in southern Malawi (Akinnifesi et al. 2006, 2007; Beedy et al. 2010). The site was in a sub-humid, unimodal rainfall region with a moderately well drained sandy clay soil. **e** Maize intercropped with a leguminous tree and pigeon pea was evaluated over four years in a field experiment at Makoka Research Station and a nearby on-farm site in southern Malawi (Chirwa et al. 2003). The sites were in a sub-humid, unimodal rainfall region with moderately well drained sandy loam to sandy clay soils

A study by Chirwa et al. (2003), also from Malawi, demonstrates the influence of management in Gliricidia tree agroforestry as reported for researcher managed on-station and farmer managed on-farm sites, all with very similar rainfall (Fig. 1e). The difference in maize yield between the farmer managed and researcher managed trial was explained in part by labor availability for pruning the Gliricidia trees. On-farm, the grain yield of maize intercropped with pigeon pea in the agroforestry system was 61% higher than with sole maize, while the corresponding protein yield increased by 246%. Introduction of a leguminous tree species into the system provided large amounts of good quality vegetative biomass and the efficient use of water resources from rainfall, which exceeded those of production systems with annual species.

Grain legume diversification

Waddington et al. (2007a) demonstrated a very clear effect of mineral fertilizer application, which more than doubled maize grain yield in a long-term (13-year) experiment that tested five different grain legume/maize row-intercropping systems in Zimbabwe (Fig. 2a; two selected for this radar chart). Fertilizer was applied only to maize, as NPK (22 kg N, 17 kg P & 16 kg K ha^{-1}) and ammonium nitrate (70 kg N ha^{-1}). Without fertilizer, the production systems with maize intercropped with pigeon pea and cowpea showed increased vegetative biomass and protein yields, and rainfall productivity was enhanced over the long term. Although maize grain yields remained similar across these treatments compared to unfertilized sole maize, this was achieved with a maize plant population density in the row-intercropped stand that was two thirds of the sole stand, which indicated that an individual maize plant may benefit from the intercrop rather than suffer due to competition for resources with the secondary crop. The legumes also contributed protein-rich grain.

Snapp et al. (2010) tested legume diversification systems with increasing intensity of the legume component in on-farm experiments in the Songani region of Malawi (Fig. 2b). These systems were identified with farmers in a participatory research approach (Snapp and Silim 2002) and included intercropping or rotation of maize with 'doubled-up' legumes, i.e. pigeon pea intercropped with groundnut. Annualized maize grain yields in the rotations were lower than for continuous cultivation of maize. However, all other parameters (including NAE) were enhanced, especially protein yield due to the presence of the legumes. In contrast, the intercropping system maintained maize grain yields while the performance of all other measured parameters was enhanced.

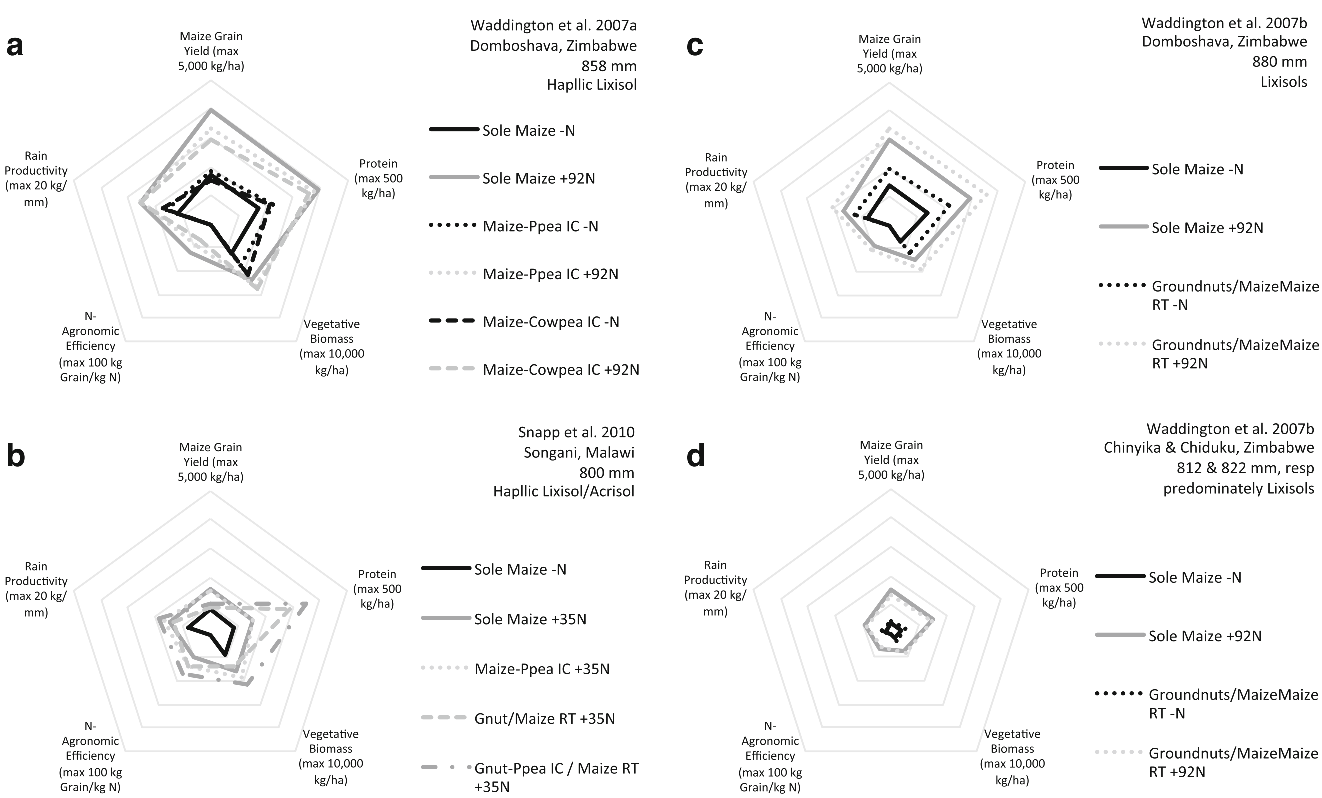
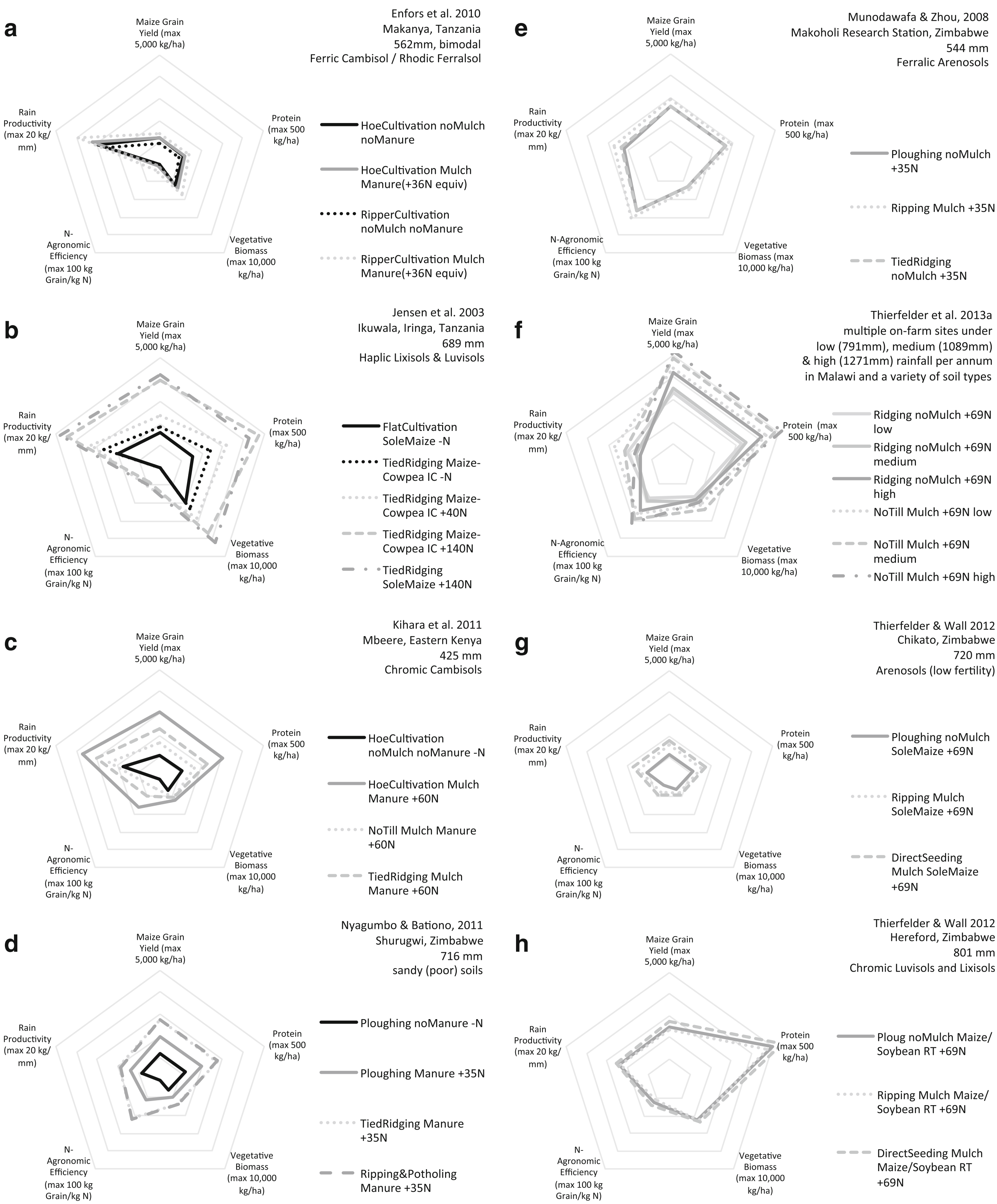


Fig. 2 Ecosystem provisioning and supporting services associated with grain legume diversification, reported in three studies conducted across sub-Saharan Africa. **a** To evaluate a range of maize-grain legume intercrops in sub-humid, unimodal Zimbabwe, a long-term researcher-managed field experiment was conducted at a sandy loam research farm site over 13 years (Waddington et al. 2007a). **b** Grain legume diversification through legume intercrops (IC) and rotations (RT) with maize was evaluated at farmer managed on-farm sites in sub-humid, unimodal southern Malawi, over two years (Snapp et al. (2010). Experiments were located at 15 sites in two communities, with moderately drained sandy to loamy soils. **c** Three cycles (9–12 years) of a groundnut-maize-maize-groundnut rotation (RT) were evaluated against continuous maize, with 92 kg/ha N applied to maize, or without fertilizer, on sandy loam soils at Domboshava research farm in sub-humid unimodal north-eastern Zimbabwe (Waddington et al. 2007b). **d** Three cycles (9–12 years) of a groundnut-maize-maize-groundnut rotation (RT) were evaluated against continuous maize, with 92 kg/ha N applied to maize, or without fertilizer, on sandy loam soils on four smallholder farms in sub-humid unimodal zones of north-eastern Zimbabwe (Waddington et al. 2007b)



Rotations of grain legumes with maize are a further diversification option for smallholder cropping systems in those parts of sub-humid southern Africa where intercrops are less common and have been discouraged among farmers. In another long-term (9–12 year) study, Waddington et al. (2007b) measured the performance of three cycles of a groundnut-maize-maize-groundnut rotation against continuous maize (with and without mineral fertilizer on maize) at a

◀ **Fig. 3** Ecosystem provisioning and supporting services associated with conservation tillage, reported in seven studies conducted across sub-Saharan Africa. **a** Conservation tillage of maize was evaluated in farmer managed experiments over five seasons at four on-farm sites with poor soil fertility in semi-arid bimodal Tanzania, comparing ripper to hand-hoe cultivation, with and without the application of mulch and manure (Enfors et al. 2011). **b** Reduced tillage tied-ridging of maize with legume intercropping was evaluated in on-farm researcher-managed experiments over three years at moderately fertile sites in Ikuwala community in semi-arid, unimodal Tanzania (Jensen et al. 2003). **c** No tillage of maize, tied-ridging and conventional practice using hand hoes with a range of mulch and nutrient management treatments was evaluated over four seasons (two years) at a sandy soil site located in semi-arid, bimodal eastern Kenya (Kihara et al. 2011). **d** Various conservation tillage practices, including ripping and potholing of maize with and without manure were evaluated in six on-farm researcher-managed experiments over three years in semi-arid, unimodal Shurugwi district in Zimbabwe, with low fertility, sandy soils the main soil type (Nyagumbo and Bationo 2011). **e** Conservation tillage of maize was tested comparing traditional ploughing with ripping plus mulching and tied ridging over three years in trials conducted on a research station in semi-arid, unimodal Zimbabwe with low fertility sandy soils (Munodawafa and Zhou 2008). **f** A conservation agriculture trial was conducted long-term in multiple on-farm sites across sub-humid, unimodal Malawi evaluating maize response under no-till with residues retained, with and without grain legumes, compared to a hand hoe control (Thierfelder et al. 2013a). Data presented are from low (5 sites), medium (2 sites) and high rainfall (2 sites) environments. The soils ranged from loamy sands to sandy clay loams, with poor to medium soil fertility. **g** A long-term conservation tillage experiment (data reported from 5 years) conducted on smallholder farms at Chikato compared maize production under ripline-seeding and direct-seeding with conventional ploughing on sandy, low fertility soils in semi-arid, unimodal Zimbabwe (Thierfelder and Wall 2012). **h** A long-term conservation tillage experiment (data reported from 5 years) conducted at Hereford Farm compared maize production under ripline-seeding and direct-seeding with conventional ploughing at a medium fertility, loamy clay site in sub-humid, unimodal Zimbabwe (Thierfelder and Wall 2012)

moderately-fertile research farm site and on highly depleted smallholder farms in sub-humid unimodal rainfall areas of eastern Zimbabwe. On the research farm (Fig. 2c), maize in rotation with groundnut greatly improved grain production and yield stability over the years, both with N fertilizer to maize (by 13%) and without N (by 42%). Protein, rain productivity and vegetative biomass in the system all increased with the rotation. Including groundnut, like other grain legumes, also improves diet diversity, human nutrition and income (if sold). Under the much poorer soil fertility conditions on farm, maize grain yields were very low but improved from an annualized value of 374 kg ha^{-1} with continuous maize to 431 kg ha^{-1} (by 15.1%) with the rotation, without the use of N fertilizer (which is common practice for farmers in those areas) (Fig. 2d).

Conservation tillage/agriculture

Enfors et al. (2011) conducted an on-farm study of conservation tillage (CT) in a semi-arid environment in Tanzania with substantial variability in rainfall and thus in crop performance (Fig. 3a). The authors reported a beneficial interaction between ripper-tine tillage, mulching to improve water availability, green manuring and applications of farm yard manure. No mineral fertilizer was applied, but N input from the manures was calculated at 36 kg N ha^{-1} based on information reported by the authors. Despite improvement to RP due to mulching, gains in grain yield were marginal and there was no improvement in yield stability over six growing seasons.

Jensen et al. (2003) conducted an experiment on farm fields in two communities of Tanzania's semi-arid Iringa region (Fig. 3b). Nine combinations of soil cultivation, cropping pattern and nutrient management were tested, with four illustrative treatments presented in Fig. 3b. Tied-ridging and intercropping with cowpea enhanced maize response to fertilizer application compared to the control (conventional cultivation of unfertilized sole maize). Very high rates of fertilizer application (140 kg N ha^{-1}) produced the highest yields, but did not improve NAE.

Kihara et al. (2011) tested combinations of tillage (conventional hoe cultivation, no-till and tied-ridging using hand hoes) and organic inputs, each with and without N fertilizer (60 kg N ha^{-1}) in semi-arid eastern Kenya (Fig. 3c). The mixed application of 1 t ha^{-1} of crop residues plus 1 t ha^{-1} of goat manure performed better than 2 t ha^{-1} of goat manure. In Fig. 3c we focus on differences due to soil cultivation methods. Applications of N raised maize grain yields in the first three of four seasons and there was a significant interaction between tillage and organic manure management in the fourth season.

Nyagumbo and Bationo (2011) conducted an on-farm experiment on CT and nutrient management in a semi-arid region of Zimbabwe over three years (Fig. 3d). Early on, the CT treatments of tied-ridging and ripping/potholing performed worse than conventional ploughing, and the authors suspected poorer mineralization of soil resources with these treatments. In the following years, when both organic inputs and mineral fertilizer were added, grain yields increased. Overall, no difference was detected between CT systems when organic and mineral fertilizers were used (Fig. 3d).

Munodawafa and Zhou (2008) conducted a similar on-station trial in an area relatively close to the site used by Nyagumbo and Bationo (2011), but 10 years earlier (Fig. 3e). Munodawafa and Zhou (2008) applied NPK mineral fertilizer as a basal dressing and N (ammonium nitrate) as a top dressing, totaling 34.5 kg N ha^{-1}. The results for maize grain, protein and vegetative biomass yields were similar to Nyagumbo and Bationo (2011), but rain productivity (RP) was slightly higher. This demonstrates the complex relationship between primary biomass production and water resource availability because the 1993/4 to 1995/6 seasons received less rainfall with higher variability (544 mm; CV 36%) compared to the 2003/4 to 2005/6 seasons (716 mm; CV 16%).

Thierfelder et al. (2013a) compared the performance of traditional (ridging by hand hoe) maize production with CA (no till, crop residue retention, maize with and without a legume intercrop) under a wide range of agro-ecological conditions in a longer-term (2005–2012) on-farm study in Malawi (Fig. 3f). The soils ranged from poor sandy soils with median annual rainfall of 1000 mm to more fertile soils with rainfall ranging from under 850 mm to above 1200 mm. All treatments received mineral fertilizer following recommendations used in Malawi's Farm Input Subsidy Program (69 kg ha^{-1} of N as 100 kg of NPK 23:21:0:+4S and 100 kg ha^{-1} of Urea 46% N). Legume grain yields were not reported and the performance of sole maize and intercropped maize was the same. Grain yield was unaffected by treatment, but the no-till and mulch treatments improved RP compared to hand-hoe ridging, under low rainfall (Fig. 3f).

Thierfelder and Wall (2012) compared conventional animal-drawn ploughing using a mouldboard plough to animal-drawn ripping (with hand-placed seeding on the ripline) and an animal-drawn direct seeding technology in a longer-term (2005/6 to 2009/10) experiment on smallholder farms at two sites in Zimbabwe (Chikato village (Fig. 3g) and Hereford Farm (Fig. 3h)). In these on-farm trials, the CA treatments included retention of crop residues on the soil surface. Chikato grew sole maize, while a maize-soybean rotation was used at Hereford. Although both sites experienced similar average annual rainfall amounts, they differed in rainfall variability (Chikato 720 mm; +/− 415 mm SD vs. Hereford 801 mm +/− 194 mm SD). Furthermore, Chikato had infertile sandy soils while the site in Hereford was dominated by more-fertile heavy clay soils. Technology performance did not differ under the more favorable growing conditions at Hereford, but ripping improved maize grain yields by 36% and direct seeding by 55% under the marginal small farm production conditions at Chikato (Fig. 3g and h).

Discussion

Maize grain yield

We focus on maize grain yield as a key metric for assessing SI technologies due to the widespread dependence of Africa's Sub-Saharan population on maize as a principle source of food energy (Shiferaw et al. 2011; Kumwenda et al. 1996). Meeting home consumption requirements for maize is top priority across much of Africa, which was why we assessed annualized maize production (Snapp et al. 2010). The use of N fertilizer increased maize grain yields in almost all studies. On its own, this raises sustainability issues since declines in maize grain yield have been observed in long-term trials with N fertilizer alone, unless complementary investments are made in inputs and practices that provide and maintain SOM (Kibunja et al. 2012; Nandwa and Bekunda 1998). In addition, substantive government subsidies are often required to assure access to N fertilizer and to ensure its use is profitable.

Rotational SI technologies were often associated with reductions in the production of maize grain relative to continuous maize, because no maize is grown during the legume phase of the rotation. In many parts of SSA, farmers have very small land holdings that pose a challenge for implementing rotation systems, even though these have often been shown to support enhanced grain yield, stability of yield, and fertilizer efficiency in the maize phase (Snapp et al. 2010, and see Figs. 1ab and 2b). There are situations where highly degraded soils and a lack of access to fertilizer minimize benefits from crop rotation. Stabilizing the system at low productivity is not a desirable outcome (Fig. 2cd, Waddington et al. 2007b). Rotations will be more attractive to farmers that are not severely constrained for land since they have the opportunity to stagger crop plantings on different fields to ensure production of some maize and some grain legume each year.

In contrast to rotational systems, maize grain yield in intercrops was maintained relative to monoculture maize (Figs. 1ce, 2b and 3b), with few exceptions (Fig. 2a). When crops are grown in the same field at the same time, the competition for light, nutrients and water resources may negatively affect the performance of the maize crop and lead to trade-offs, as illustrated by the Waddington et al. (2007a) study. Planting system arrangement in an intercrop matters; i.e. whether a substitutive or additive design is used. In Waddington et al. (2007a) an individual maize plant intercropped with pigeon pea produced 29% more grain than an individual plant in a sole maize stand when both received fertilizer, but the substitutive intercrop planting pattern they employed led to reduced overall maize yields on an area basis in some cases (although the legume provided nutritious grain as well). With unfertilized maize (which is a common smallholder practice in Zimbabwe and many other parts of SSA), plants yielded 61% more when intercropped and thus compensated for the lower planting density (Waddington et al. 2007a). Agroforestry intercrops produced substantially higher maize grain yields than all other studies; 2000 to 5000 kg ha^{-1} of grain relative to ~1000 kg ha^{-1} of sole maize (Fig. 1de). However, the labor requirement to intercrop Gliricidia with maize is high (Akinnifesi et al. 2006; Akinnifesi et al. 2007; Makumba et al. 2007), which can lead to difficulties with implementation on a large area and to conflicts for labor with other farm activities.

Conservation tillage (CT) produced inconsistent maize grain yields relative to conventional tillage methods (hand hoe or animal-drawn plough). Kihara et al. (2011) (Fig. 3c) found reduced yields with CT, whereas Enfors et al. (2011) and Munodawafa and Zhou (2008) saw that yields remained essentially the same (Fig. 3ae). Other studies reviewed here report higher yields under CT relative to conventional tillage

(Nyagumbo and Bationo 2011; Thierfelder and Wall 2012; Thierfelder et al. 2013a; Fig. 3dfg). Additionally, reduced tillage techniques allow for earlier planting in the crop season, a practice which is often associated with yield gains (Haggblade and Tembo 2003; Shumba et al. 1992). Since such effects are related to the broader farm management system, they may be overlooked in conventional field trials alone. These variable results are similar to previous assessments where it was found that many factors such as rainfall patterns, edaphic environments, crop species, rotational diversity, crop residue management and increased weed pressure (which is common during early years of adoption) may all influence yield performance in CT systems (Chuma and Hagmann 1995; Giller et al. 2009; Thierfelder et al. 2013b).

Generally, the field studies reviewed here indicate that it can often take multiple years before yields of maize grain are noticeably altered by SI technologies. The gains in maize yield observed in agroforestry systems and under some types of CT relative to conventional tillage were seen only after three or more years. Since improvements to soil quality take time to accrue and to translate into higher crop yields, well-targeted subsidies may be required to support farmers investing in the seeds, fertilizer and weed control needed to transition to SI systems.

Protein

In addition to the production of carbohydrates, evaluating protein yields in crop systems is of considerable interest to development practitioners and communities (Smith et al. 2006). This has raised the profile of SI technologies that produce protein-dense grain to help diversify diets. Many of the SI options we reviewed included food legumes, which were the source of the increased protein yields shown in Figs. 1abe and 2a-d. Gains in protein yields were also observed for SI inputs and practices that enhanced soil fertility, with a subsequent increase in the quantity of maize grain protein due to the better soil; in some cases these were modest (Fig. 1ac), in others substantial (Fig. 1de). Intercropping unfertilized maize with grain legumes increased protein yields compared to sole maize stands (see Fig. 2a, as well as Figs. 1ce and 2b) and similar increments in protein are possible through some maize-grain legume rotations (Fig. 2cd). This is important because it shows it is possible to enhance the production of protein without requiring large investments in subsidized mineral fertilizer, which has widespread relevance to many of the most resource-constrained smallholder farmers and governments in Africa.

Several of the papers we reviewed did not report legume yields, a major limitation given the goals of those studies (Thierfelder et al. 2012; Thierfelder et al. 2013a; Thierfelder et al. 2013b). Personal communication with the authors indicated that legume yields from these on-farm trials were often very low due to poor crop stand establishment, pest damage, and the loss of grain legumes occurred due to inadequate control of livestock, crop sales before measurement, or theft. These hazards are challenges particularly associated with the production of nutrient-dense legume crops, which are attractive to pests and require detailed agronomic knowledge and practice to achieve superior production (Snapp et al. 2002b).

Vegetative biomass

Agroforestry and green manure systems are expected to add substantial amounts of high quality biomass, however differences between species can be substantial and the productivity potential of the environment matters (Chamshama et al. 1998). Some of the green manure systems we reviewed – which included pigeon pea and mucuna – produced large amounts of biomass (Fig. 1ac) comparable to that produced by agroforestry species (Fig 1de), although not in all cases (Fig. 1b). Overall, biomass was very high in maize-Gliricidia agroforestry intercrop systems (Fig. 1de), and moderately high in maize-grain legume systems compared to sole maize (Fig. 2a-d).

Maize stover biomass was increased by N fertilizer, similar to the effects on grain yield and protein (Figs. 1b-d, 2a-d and 3b-d). The critical role of N fertilizer in producing sufficient maize stover to cover soil was highlighted in a recent assessment of CA in sub-Saharan Africa (Vanlauwe et al. 2014). However, growing sole maize with large amounts of N (≥50 kg ha^{-1} N) to produce soil mulch is not an efficient use of resources, since such sole maize systems in our review yielded only modest amounts of biomass (2000 to 4000 kg ha^{-1}) even when fertilized (Figs. 1a-c, 2acd and 3cg). In contrast, far larger amounts of biomass (>7000 kg ha^{-1}) were produced by diversified maize-legume systems (Fig. 1a and c-e) and, importantly, the biomass was of higher quality.

Because increasing the production of vegetative biomass (especially from deep rooted legumes) is one of the few practices available to replenish N, build SOM and control soil erosion, it was surprising to us how difficult it was to find field studies that measured the aboveground biomass produced by technologies that may contribute to SI. A recent review of carbon sequestration potential through agroforestry systems in Africa noted the substantial site-to-site variation in biomass produced, and the scarcity of data sets on biomass (Nair and Nair 2014).

Nitrogen agronomic efficiency

Maize yield responded positively to N fertilizer in all the studies we assessed, but the efficiency of use of the N applied varied substantially. In a review on agronomic fertilizer efficiency in African cropping systems, Vanlauwe et al. (2011) reported yield responses that ranged from 15 to 30 kg maize grain per kg N applied for farmer- and researcher-led fertilizer trials. This was similar to the range we observed here. Green manure systems (Fig. 1ad) in particular show potential to greatly improve NAE (to 47 and 87 kg grain per kg N applied in the two studies), underscoring their value for soil rehabilitation.

In grain legume-diversified systems, patterns of planting the crops impact on the efficiency of N fertilizer use. NAE in a pigeon pea maize intercrop and a groundnut maize rotation were increased by 42% compared to the sole maize crop (Fig. 2b). Further increasing the legume component through a groundnut-pigeon pea 'doubled-up' legume intercrop in rotation with maize enhanced NAE by another 37% (79% above sole maize, Fig. 2b) (Snapp et al. (2010). In contrast, Waddington et al. (Waddington et al. 2007a; Fig. 2a) found NAE reduced for maize grown at high fertilizer rates when intercropped with cowpea (by 46%) or pigeon pea (25%). Relay intercrop arrangements with green manure legumes may offer the best alternative to exploit crop complementarity. Fofana et al. (2004) found the grain yield of unfertilized maize following a mucuna relay intercrop increased to the same level as fertilized sole maize at 50 kg of N ha^{-1} (2250 vs. 2200 kg ha^{-1}, respectively), while in the previous season fertilized maize produced double the amount of grain compared to the intercropped treatment (1200 vs. 600 kg ha^{-1}, respectively). Furthermore, even at high rates of N application, site conditions matter. NAE in a groundnut-maize rotation improved with moderate soil fertility (24% above sole maize) while the NAE was reduced (−15%) under marginal conditions (Fig. 2cd). In a large study with thousands of smallholder farmers over several years across semi-arid areas of Zimbabwe, Twomlow et al. (2010) showed that small amounts of N fertilizer (17 kg N ha^{-1}) commonly resulted in 15–45 kg of grain per kg of N input, profitably raising maize and sorghum grain yields by 30–50%. In our review, the Tanzania study by Jensen et al. (2003) (Fig. 3b) showed that NAE remained around 19 kg grain per kg N fertilizer regardless of whether N was applied at 40 kg N ha^{-1} or 140 kg N ha^{-1}. This implies that gains in NAE with increasing application rates of N may be limited by other nutrients or growing conditions (including water deficits).

Field soil characteristics matter (see Fig. 2cd), as well as management history and practice, since all impact on NAE. For a sub-humid smallholder farming area in Zimbabwe, Zingore et al. (2007) found that NAE for maize was much higher on sandy soil infields that had long-received organic inputs and mineral NP fertilizer compared to sandy outfields that had been severely depleted of nutrients and SOM. Similar findings on variable NAEs by field type and management history have been reported in studies in East Africa (e.g. Tittonell et al. 2008) and West Africa (Wopereis et al. 2006) and these demonstrate that there are widespread opportunities to enhance NAE through suitable management at the farm scale.

Furthermore, tillage practices need to be well adapted to specific locations and management capacities to maintain or improve NAE. In the studies reviewed here we observed positive effects (Fig. 3dfg), but also negative (Fig. 3c) or no effects (Fig. 3eh) of reduced tillage on N-fertilizer efficiencies.

Rainfall productivity

Consistent effects of seasonal rainfall were rarely discernible for crop grain yields or biomass produced. In addition to total amount of rainfall, its distribution during the cropping season, surface runoff, evaporation from the soil surface, and soil water holding capacity are all expected to affect rainfall productivity (RP). We found a large amount of variation in RP between and within studies, associated with variations in soil and rainfall. For example, maize achieved higher RP in eastern Kenya with 425 mm of annual rainfall (Fig. 3c; $RP_{HoeCultivation\ noMulch\ noManure\ \text{-}N}$ = 6.9 kg mm^{-1} and $RP_{HoeCultivation\ Mulch\ Manure\ +60N}$ = 14.8 kg mm^{-1}) than in Togo with 824 mm (Fig. 1c; $RP_{SoleMaize\ \text{-}N}$ = 1.9 kg mm^{-1} and $RP_{SoleMaize\ +50N}$ = 4.1 kg mm^{-1}) or in Ghana at 1271 mm (Fig. 1a; $RP_{SoleMaize\ \text{-}N}$ = 4.0 kg mm^{-1} and $RP_{SoleMaize\ (+60N\ in\ season4)}$ = 4.7 kg mm^{-1}). Enfors et al. (2011) (Fig. 3a) recorded only marginal improvements from ripping combined with mulch and manure under rainfed conditions but when supplemental irrigation from water harvesting was provided, maize grain yield improved on average by 94% during the three seasons tested.

Generally, the studies reviewed here suggest that crop production can be reduced both by excessive (e.g. >1000 mm; Fig. 1ade) and low (e.g. < 500 mm, Fig. 3c) annual rainfall conditions in the absence of appropriate soil and water management practices. The intensity and timing of rainfall events may produce flooded conditions that markedly reduce crop yields in the semi-arid to sub-humid tropics. For example, RP was lower in both high and low rainfall years in the maize-grain legume intercrop systems studied in Zimbabwe (Waddington et al. 2007a; Fig. 2a), whereas RP was highest in no-till, low rainfall sites in another Zimbabwe on-farm study (Thierfelder et al. 2013a: Fig. 3f). In contrast, in their Zimbabwe study Nyamgumbo and Bationo (Nyagumbo and Bationo 2011; Fig. 3d) found no differences in RP for tied ridging versus ploughing. Although the tied-ridging tillage systems studied by Jensen et al. (2003) improved total dry matter production with and without an intercrop in years with normal rainfall amounts (500–600 mm) and distribution, negative effects were observed for tied ridging in seasons with high rainfall (700–900 mm). Factors that reduce the feasibility and sustainability of tied ridging are the labor needed for their timely management and the risk of building up a hoe pan (as experienced in Malawi; Materechera and Mloza-Banda (1997)).

Thierfelder et al. (2013a) demonstrated overall benefits of zero-tillage and mulching with crop residues in several locations in southern Africa, but high rainfall was often associated with negative yield responses to the CT practices, particularly in the initial years of implementation (Thierfelder and Wall 2012). Shumba et al. (1992), working with ripper-tine reduced tillage in Zimbabwe, also found that high rainfall (around maize flowering) was associated with lower maize yields with tine tillage compared with conventional ploughing, while more moderate rainfall over this period (the more common situation) was linked to higher yields. Generally, it appears that the most efficient use of rainfall may be achieved when moderate amounts of rainfall are distributed favorably during the cropping season (Fig. 3c); a condition less likely to occur in many parts of SSA due to the effects of climate change (Pauw et al. 2011). Hence, successful SI will often depend on the ability of farmers to better manage water resources from seasonal rainfall.

Overall performance and tradeoffs

In sum, we found that the application of N fertilizer consistently improved grain yield production markedly, and all the other services measured at least in a moderate manner. The positive response of cereal grain yield to N has been shown in numerous studies, although response to other services has rarely been monitored (see e.g. Waddington et al. 2007b; Twomlow et al. 2010; Rusinamhodzi et al. 2011; Vanlauwe et al. 2014). The one exception to high N-fertilizer effectiveness was for sites with very low SOM, often sandy-textured; these were represented by three Zimbabwe sites in this review and the non-responsiveness of these soil types is the subject of on-going research (Kurwakumire et al. 2015). A key finding was that inclusion of multi-purpose, longer-lived legumes in green manure- and grain legume-diversified systems was consistently associated with high N fertilizer efficiency, protein production, vegetative biomass and fertilizer response under smallholder farm conditions.

Tradeoffs were apparent in our study: technologies that included mulch or green manure were able to provide a broad range of ecosystem services, yet rarely were able to optimize all, and maize yield was often inversely related to other services. An example is the green manure agroforestry systems with Gliricidia. Although a prolific producer of high quality biomass, free-roaming livestock and labor-demands for pruning have often prevented its adoption. Crop farming practices cannot be viewed in isolation and instead need to be integrated into the overall livelihood system of smallholder farmers. In particular their compatibility with livestock husbandry and complementarity with other natural resource management practices have to be addressed case by case. Livestock control during much of the year is an important prerequisite for growing many forms of green manure and multipurpose crops such as pigeonpea. Further, substantial reductions in maize yield will occur unless sufficient and well-timed prunings are conducted in mixed tree-crop systems (Versteeg et al. 1998). In contrast, maize-mucuna systems are weed-suppressive and thus can reduce labor requirements, which contributed to their adoption in Benin (Versteeg et al. 1998). Various studies in eastern and southern Africa (including Nyende and Delve (2004) in Uganda, Mhango et al. (2013) in northern Malawi and Kamanga et al. (2014) in central Malawi have highlighted the much greater interest by farmers in multipurpose legumes that provide food plus some soil fertility benefits, such as pigeon pea and groundnut, compared to species used only for green manure. Promiscuous soybean is another annual legume that has been increasingly accepted by smallholder farmers in southern Africa in the last decade for grain production that may also help maintain soil fertility (Giller et al. 2011a).

Benefits from green manures and rotational grain legume systems are particularly important to use in combination with other technologies, such as in the rehabilitation of degraded soils. Furthermore, rotational systems may confer other ecosystem services not captured here such as pest regulation and resilience to rainfall variability (Shennan 2008). The unique benefits we found to derive from intercropping concur with findings from several studies which showed that mixtures of long-lived legumes intercropped with maize can improve grain and protein yield, resource use efficiency (including mineral N fertilizer and rainfall) and soil fertility in SSA smallholder maize-based farming (e.g. Snapp et al. 2010; Glover et al. 2012). There is also compelling evidence that many legume species enhance N input into soil through N fixation as well as the availability of P to cereal crops when grown as intercrops (Li et al. 2007) suggesting that intercropping with indeterminate, multipurpose legumes may be a critical early component of SI for improved NAE, RP, protein production and system sustainability. Nevertheless, intercropping is a complex farming practice that is knowledge intensive, with many biological and economic barriers to farmers growing more legumes (Snapp et al. 2002a, 2002b; Snapp et al. 2010).

For smallholder farming, CT practices primarily aim to raise soil moisture to sustain plant growth (Thierfelder and Wall 2009), but the studies we reviewed showed variable results in this regard. Maize grain yield, vegetative biomass production and rain water utilization were improved in some cases but not in others, indicating the need for site specific adaptation. Importantly for food security of African smallholders, yield penalties in wet years under CT practices appear to be smaller than yield gains in dry years (Hussain et al. 1999; Rusinamhodzi et al. 2011). Our findings are supported by recent reviews of CA on smallholder farms in southern Africa (Andersson and D'Souza 2014) and globally (Brouder and Gomez-Macpherson 2014). The observed variability of RP and high variation in yield performance across sites in response to CT and related practices has been repeatedly reported (e.g. Pretty et al. 2011; Rusinamhodzi et al. 2011). In a meta-analysis of findings, Rusinamhodzi et al. (2011) also noted the requirement for large doses of N fertilizer to achieve maize yield gains under CT in the early years of adoption. This is related to nutrient immobilization associated with low quality crop residues, which is widespread on smallholder farms in SSA. Because of this Vanlauwe et al. (2014) have questioned the identification of CT on its own as a viable low-input, ecological intensification technology. To improve the quality of crop residues, diversification with legumes has been included as a theme within CA. However, the control of weeds in mixed maize-legume systems continues to pose challenges in CA research trials (on whether or not to use herbicides to control the many weeds that often appear with maize when farmers begin to use CT) and may restrict smallholder adoption (Giller et al. 2009). Andersson and D'Souza (2014) concluded that successful CA requires assured access to input and output markets to support the use of N fertilizer and herbicides. Our assessment is consistent with many of these earlier findings that CA must be locally adapted to take into account soil type, micro-topography and climate and that it requires substantial investment in farmer capacity building as well as the development of input and output markets.

In conclusion, based on the studies we have reviewed, the use of N fertilizer and diversification with multipurpose legumes (especially in intercrops) were crucial components to producing a range of (agro)ecosystem services associated with the sustainable intensification of African smallholder maize-based cropping systems. In many cases these practices can be used in combination with site-specific resource-conserving CT techniques. The uptake and use of these SI interventions will be facilitated when farmers have good access to finance, productive land and labor, and will be easier when farmers can expect rapid returns on their investment (as with N fertilizer and grain legumes) rather than delayed returns experienced with CT (Thierfelder and Wall 2012; Rusinamhodzi et al. 2011). Diversification with grain legumes is more likely when there is strong household demand for their use as food and when produce markets are available locally; enabling conditions that have become more common in SSA in recent years (e.g. Ajayi et al. 2007; Mhango et al. 2013; Kamanga et al. 2014).

Ways forward

We found relatively few (17) published studies on SI technologies from smallholder maize-based farms in SS Africa that were multi-year/multi-site and that reported data directly related to multiple ecosystem services beyond the provisioning services of crop yields. Hence we used proxies for services to gauge the potential that SI technologies hold in reducing surface runoff, increasing water holding capacity and improving response to the application of N fertilizer. This modest evidence base needs to be augmented with long-term, multi-site experiments that quantify factors contributing to multiple services from key SI cropping systems, for example SOM content and quality, and the fraction of plant available water from rainfall. There is also a need to move to a more systematic assessment of socio-economic issues such as adoptability in relation to SI strategies.

Many studies on SI in SSA have called for the integrated management of organic inputs and mineral nutrients (e.g. Snapp et al. 1998; Pretty et al. 2011) and our assessment supports their greater use in maize systems. We further suggest that intercrops with multi-purpose legumes that produce protein-rich food, leafy vegetative biomass and provide soil N are a critical early component to support SI. Plant breeding efforts are needed to develop legume varieties with deep root systems, indeterminate growth patterns and long-lived traits that combine copious vegetation with food products. These are attributes that contribute to food security in the near-term while providing biomass for soil quality, RP and fodder. Examples of species that are grown as food crops in some parts of SSA that could be selected for multi-purpose properties include: pigeon pea (*Cajanus cajan*), scarlet runner bean (*Phaseolus coccineus* L.) and lablab (*Lablab purpureus* L, synonym: *Dolichos purpureus*). Longer-lived growth habit genotypes of cowpea (*Vigna unguiculata* L.), jackbean (*Canavalia ensiformis* L.), and climbing types of common bean (*Phaseolus vulgaris* L.) are other examples (Glover et al. 2012; Douxchamps et al. 2014; Guretzki and Papenbrock 2014). Very little crop improvement attention has focused on multi-purpose types of legumes that enhance both grain and vegetative biomass (Giller et al. 2011a) and far more should be done. Plant breeding investments could also improve the food quality properties of non-standard legume grains (Nyende and Delve 2004; Aguilera et al. 2013), such as by removing L-dopa from mucuna seed to expand its use beyond its current role as a minor food in countries such as Malawi, Nigeria and India (Pugalenthi et al. 2005).

Based on our findings, various SI technologies may be successfully combined to form complex smallholder maize-based cropping systems, but the large variability in performance observed in these studies of SI technologies, particularly for CT, needs to be addressed. Site specific agro-ecological conditions and the local socio-economic context have to be taken into account for best performance and uptake. So, instead of promoting fixed SI interventions, the best approach may be to provide farmers with a range of 'best bet and best fit' crop diversification and integrated nutrient management options, and then build farmer capacity to effectively combine these SI components with locally adapted soil cultivation practices by encouraging co-learning and innovation in cropping systems (Snapp et al. 2002a; Giller et al. 2011b; Coe et al. 2014; Giller et al. 2015). Support for participatory on-farm research and extension over the long-term is crucial given the very high site specificity of maize and soil responses observed here (and see Andersson and Giller 2012).

Finally, the foregoing adaptation and promotion of SI interventions will be far more successful if it can be better aligned with appropriate policy support. Under the CAADP pillar on Sustainable Land and Water Management (Bwalya et al. 2009), diversified SI approaches and CA technology packages have found their way into national policy frameworks, for example in Rwanda, Zambia and Malawi. However, many shortcomings remain in their implementation. For example, practitioners observed recent inconsistencies in policy implementation in Rwanda, when official directives in support of monocultures (through mandatory uprooting of intercrops) undermined existing sustainable smallholder farming systems (Isaacs et al. 2016). Similarly, the Zambian and Malawian farm input subsidy programs tend to focus on the distribution of hybrid maize seed and maize fertilizer at the expense of legume diversification, agronomy training and related sustainable farming practices. Thus more appropriate and consistent policy support is urgently required for farmer adaptation of suitable SI interventions and their incorporation into African maize farming.

Acknowledgements We thank Emily May and Danielle Zoellner for help with literature citing and data preparation, as well as Regis Chikowo and five anonymous reviewers for their suggestions on drafts of this paper. A substantial part of the work was carried out while the lead author was affiliated with the International Food Policy Research Institute's Malawi country program using funds from Irish Aid Malawi. Further financial support was provided by United States Agency for International Development - Feed the Future, through the Africa RISING project of the International Institute for Tropical Agriculture.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Adjei-Nsiah, S., Kuyper, T. W., Leeuwis, C., Abekoe, M. K., & Giller, K. E. (2007). Evaluating sustainable and profitable cropping sequences with cassava and four legume crops: effects on soil fertility and maize yields in the forest/savannah transitional agro-ecological zone of Ghana. *Field Crops Research, 103*, 87–97.

Aguilera, Y., Diaz, M. F., Jimenez, T., Benitez, V., Herrera, T., Cuadrado, C., Martin-Pedrosa, M., & Martin-Cabrejas, M. A. (2013). Changes in nonnutritional factors and antioxidant activity during germination of nonconventional legumes. *Journal of Agriculture and Food Chemistry, 61*, 8120–8125.

Ajayi, O. C., Akinnifesi, F. K., Sileshi, G., & Chakeredza, S. (2007). Adoption of renewable soil fertility replenishment technologies in the southern African region: lessons learnt and the way forward. *Natural Resources Forum, 31*, 306–317.

Ajayi, O. C., Place, F., Akinnifesi, F. K., & Sileshi, G. W. (2011). Agricultural success from Africa: the case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe). *International Journal of Agricultural Sustainability, 9*, 129–136.

Akinnifesi, F. K., Makumba, W., & Kwesiga, F. R. (2006). Sustainable maize production using gliricidia/maize intercropping in southern Malawi. *Experimental Agriculture, 42*, 441–457.

Akinnifesi, F. K., Makumba, W., Sileshi, G., Ajayi, O. C., & Mweta, D. (2007). Synergistic effect of inorganic N and P fertilizers and organic inputs from *Gliricidia sepium* on productivity of intercropped maize in southern Malawi. *Plant and Soil, 294*, 203–217.

Andersson, J. A., & D'Souza, S. (2014). From adoption claims to understanding farmers and contexts: a literature review of conservation agriculture (CA) adoption among smallholder farmers in southern Africa. *Agriculture, Ecosystems and Environment, 187*, 116–132.

Andersson, J. A., & Giller, K. E. (2012). On heretics and God's blanket: contested claims for conservation agriculture and the politics of its promotion in African smallholder farming. In J. Sumberg & J. Thompson (Eds.), *Contested agronomy: agricultural research in a changing world* (pp. 22–46). New York: Routledge, Taylor and Francis Group.

Beddington, J. (2010). Food security: contributions from science to a new and greener revolution. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences, 365*, 61–71.

Beedy, T. L., Snapp, S. S., Akinnifesi, F. K., & Sileshi, G. W. (2010). Impact of *Gliricidia sepium* intercropping on soil organic matter fractions in a maize-based cropping system. *Agriculture, Ecosystems and Environment, 138*, 139–146.

Boserup, E. (1965). *The conditions of agricultural growth: the economics of agrarian change under population pressure*. Chicago: Aldine.

Brouder, S. M., & Gomez-Macpherson, H. (2014). The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. *Agriculture, Ecosystems and Environment, 187*, 11–32.

Bwalya, M., Diallo, A. A., Phiri, E., & Hamadoun, M. (2009). *Sustainable land and water management: the CAADP Pillar1 framework*. Midrand: The Comprehensive Africa Agriculture Development Programme (CAADP).

Cassman, K. G. (1999). Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America, 96*, 5952–5959.

Chamshama, S. A. O., Mugasha, A. G., Klovstad, A., Haveraaen, O., & Maliondo, S. M. S. (1998). Growth and yield of maize alley cropped with *Leucaena leucocephala* and *Faidherbia albida* in Morogoro, Tanzania. *Agroforestry Systems, 40*, 215–225.

Chartres, C. J., & Noble, A. (2015). Sustainable intensification: overcoming land and water constraints on food production. *Food Security, 7*(2), 235–245.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Nyamadzawo, G., & Giller, K. E. (2003). Nitrate-N dynamics following improved fallows and maize root development in a Zimbabwean sandy clay loam. *Agroforestry Systems, 59*, 187–195.

Chikowo, R., Mapfumo, P., Nyamugafata, P., & Giller, K. E. (2004). Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. *Agriculture, Ecosystems and Environment, 102*, 119–131.

Chirwa, P. W., Black, C. R., Ong, C. K., & Maghembe, J. A. (2003). Tree and crop productivity in gliricidia/maize/pigeonpea cropping systems in southern Malawi. *Agroforestry Systems, 59*, 265–277.

Chuma, E., & Hagmann, J. (1995). Summary of results and experiments from on-station and on-farm testing and development of conservation tillage systems in semi-arid Masvingo. In S. Twomlow, J. Ellis-Jones, J. Hagmann, & H. Loos (Eds.), *Soil and water conservation for smallholder farmers in semi-arid Zimbabwe: transfers between research and extension* (pp. 61–69). Harare: Integrated Rural Development Programme.

Coe, R., Sinclair, F., & Barrios, E. (2014). Scaling up agroforestry requires research 'in' rather than 'for' development. *Current Opinion in Environmental Sustainability, 6*, 73–77.

Daily, G. C., & Matson, P. A. (2008). Ecosystem services: from theory to implementation. *Proceedings of the National Academy of Sciences of the United States of America, 105*, 9455–9456.

Dixon, J. A., Gulliver, A., & Gibbon, D. (2001). Farming systems and poverty: improving farmers' livelihoods in a changing world (summary). In M. Hall (Ed.), *Farming systems and poverty: improving farmers' livelihoods in a changing world* (p. 407). Rome: FAO & World Bank.

Dorward, A., & Chirwa, E. (2011). The Malawi agricultural input subsidy programme: 2005/06 to 2008/09. *International Journal of Agricultural Sustainability, 9*, 232–247.

Douxchamps, S., Rao, I. M., Peters, M., Van der Hoek, R., Schmidt, A., Martens, S., Polania, J., Mena, M., Binder, C. R., Scholl, R., Quintero, M., Kreuzer, M., Frossard, E., & Oberson, A. (2014). Farm-scale tradeoffs between legume use as forage versus green manure: the case of *Canavalia brasiliensis*. *Agroecology and Sustainable Food Systems, 38*, 25–45.

Drinkwater, L. E., Wagoner, P., & Sarrantonio, M. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature, 396*, 262–265.

Enfors, E., Barron, J., Makurira, H., Rockstrom, J., & Tumbo, S. (2011). Yield and soil system changes from conservation tillage in dryland farming: a case study from north eastern Tanzania. *Agricultural Water Management, 98*, 1687–1695.

Fischer, G., Shah, M., Tubiello, F. N., & van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences, 360*, 2067–2083.

Fofana, B., Breman, H., Carsky, R. J., Van Reuler, H., Tamelokpo, A. F., & Gnakpenou, D. (2004). Using mucuna and P fertilizer to increase maize grain yield and N fertilizer use efficiency in the coastal savanna of Togo. *Nutrient Cycling in Agroecosystems, 68*, 213–222.

Fowler, R., & Rockstrom, J. (2001). Conservation tillage for sustainable agriculture - an agrarian revolution gathers momentum in Africa. *Soil Tillage Research, 61*, 93–107.

Funk, C., Dettinger, M. D., Michaelsen, J. C., Verdin, J. P., Brown, M. E., Barlow, M., & Hoell, A. (2008). Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proceedings of the National Academy of Sciences of the United States of America, 105*, 11081–11086.

Garrity, D. P., Akinnifesi, F. K., Ajayi, O. C., Weldesemayat, S. G., Mowo, J. G., Kalinganire, A., Larwanou, M., & Bayala, J. (2010). Evergreen agriculture: a robust approach to sustainable food security in Africa. *Food Security, 2*, 197–214.

Gilbert, R. A. (2004). Best-bet legumes for smallholder maize-based cropping systems of Malawi. In M. Eilitta, J. Mureithi, & R. Derpsch (Eds.), *Green manure/cover crop Systems of Smallholder Farmers: experiences from tropical and subtropical regions* (pp. 153–174). Dordrecht: Kluwer.

Giller, K. E. (2001). *Nitrogen fixation in tropical cropping systems*. Wallingford: CABI.

Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Research, 114*, 23–34.

Giller, K. E., Murwira, M. S., Dhliwayo, D. K. C., Mafongoya, P. L., & Mpepereki, S. (2011a). Soyabeans and sustainable agriculture in southern Africa. *International Journal of Agricultural Sustainability, 9*, 50–58.

Giller, K. E., Tittonell, P., Rufino, M. C., van Wijk, M. T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E. C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W. J., Sanogo, O. M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'Ungu, J., Mwale, M., Nwaga, D., Pacini, C., & Vanlauwe, B. (2011b). Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems, 104*, 191–203.

Giller, K. E., Andersson, J. A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., & Vanlauwe, B. (2015). Beyond conservation agriculture. *Frontiers in Plant Science*. doi:10.3389/fpls.2015.00870.

Glover, J. D., Reganold, J. P., & Cox, C. M. (2012). Plant perennials to save Africa's soils. *Nature, 489*, 359–361.

Godfray, H. C. J. (2015). The debate over sustainable intensification. *Food Security, 7*(2), 199–208.

Gregorich, E. G., Drury, C. F., & Baldock, J. A. (2001). Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Canadian Journal of Soil Science, 81*, 21–31.

Guretzki, S., & Papenbrock, J. (2014). Characterization of *Lablab purpureus* regarding drought tolerance, trypsin inhibitor activity and cyanogenic potential for selection in breeding programmes. *Journal of Agronomy and Crop Science, 200*, 24–35.

Haggblade, S., & Tembo, G. (2003). *Early evidence on conservation agriculture in Zambia. A paper prepared for the international workshop on "reconciling rural poverty and resource conservation: identifying relationships and remedies"*. Ithaca: Cornell University.

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences, 363*, 543–555.

Hussain, I., Olson, K., & Ebelhar, S. A. (1999). Impacts of tillage and no-till on production of maize and soybean on an eroded Illinois silt loam soil. *Soil and Tillage Research, 52*(1–2), 37–49.

Isaacs, K. B., Snapp, S. S., Chung, K., & Waldman, K. B. (2016). Assessing the value of diverse cropping systems under a new agricultural policy environment in Rwanda. *Food Security, 8*(3), 491–506.

Jensen, J. R., Bernhard, R. H., Hansen, S., McDonagh, J., Moberg, J. P., Nielsen, N. E., & Nordbo, E. (2003). Productivity in maize based cropping systems under various soil-water-nutrient management strategies in a semi-arid, alfisol environment in East Africa. *Agricultural Water Management, 59*, 217–237.

Kamanga, B. C. G., Kanyama-Phiri, G. Y., Waddington, S. R., Almekinders, C., & Giller, K. E. (2014). Evaluation and adoption of annual legumes by smallholder maize farmers for soil fertility maintenance and food diversity in Central Malawi. *Food Security, 6*(1), 45–59.

Kassam, A., Friedrich, T., Shaxson, F., & Pretty, J. (2009). The spread of conservation agriculture: justification, sustainability and uptake. *International Journal of Agricultural Sustainability, 7*, 292–320.

Keating, B. A., Carberry, P. S., Bindraban, P. S., Asseng, S., Meinke, H., & Dixon, J. (2010). Eco-efficient agriculture: concepts, challenges, and opportunities. *Crop Science, 50*, S109–S119.

Kibunja, C. N., Mwaura, F. B., Mugendi, D. N., Gicheru, P. T., Wamuongo, J. W., & Bationo, A. (2012). Strategies for maintenance and improvement of soil productivity under continuous maize and beans cropping system in the sub-humid highlands of Kenya: case study of the long-term trial at Kabete. In A. Bationo, B. Waswa, J. Kihara, I. Adolwa, B. Vanlauwe, & K. Saidou (Eds.), *Lessons learned from long-term soil fertility management experiments in Africa* (pp. 59–84). Dordrecht: Springer.

Kihara, J., Bationo, A., Mugendi, D. N., Martius, C., & Vlek, P. L. G. (2011). Conservation tillage, local organic resources and nitrogen fertilizer combinations affect maize productivity, soil structure and nutrient balances in semi-arid Kenya. *Nutrient Cycling in Agroecosystems, 90*, 213–225.

Kumwenda, J. D. T., Waddington, S. R., Snapp, S. S., Jones, R. B., & Blackie, M. J. (1996). *Soil fertility management research for the maize cropping systems of smallholders in southern Africa: a review. Natural Resources Group Paper 96–02* (p. 35). Mexico DF: CIMMYT.

Kurwakumire, N., Chikowo, R., Zingore, S., Mapfumo, P., Mtambanegwe, F., Johnston, A., & Snapp, S. S. (2015). Nutrient management strategies on heterogeneously fertile granitic-derived soils in sub-humid Zimbabwe. *Agronomy Journal, 107*, 1068–1076.

Li, L., Li, S. M., Sun, J. H., Zhou, L. L., Bao, X. G., Zhang, H. G., & Zhang, F. S. (2007). Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. *Proceedings of the National Academy of Sciences of the United States of America, 104*, 11192–11196.

Mafongoya, P. L., Bationo, A., Kihara, J., & Waswa, B. S. (2006). Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling in Agroecosystems, 76*, 137–151.

Makumba, W., Akinnifesi, F. K., Janssen, B., & Oenema, O. (2007). Long-term impact of a gliricidia-maize intercropping system on carbon sequestration in southern Malawi. *Agriculture, Ecosystems and Environment, 118*, 237–243.

Materechera, S. A., & Mloza-Banda, H. R. (1997). Soil penetration resistance, root growth and yield of maize as influenced by tillage system on ridges in Malawi. *Soil Tillage Research, 41*, 13–24.

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural intensification and ecosystem properties. *Science, 277*, 504–509.

Mhango, W. G., Snapp, S. S., & Phiri, G. Y. K. (2013). Opportunities and constraints to legume diversification for sustainable maize production on smallholder farms in Malawi. *Renewable Agriculture and Food Systems, 28*(3), 234–244.

Morris, M., Kelly, V. A., Kopicki, R. J., & Byerlee, D. (2007). *Fertilizer use in African agriculture: lessons learned and good practice guidelines*. Washington DC: The World Bank 144 p.

Munodawafa, A., & Zhou, N. (2008). Improving water utilization in maize production through conservation tillage systems in semi-arid Zimbabwe. *Physics and Chemistry of the Earth, 33*, 757–761.

Nair, P. K. R., & Nair, V. D. (2014). 'solid–fluid–gas': the state of knowledge on carbon-sequestration potential of agroforestry systems in Africa. *Current Opinion in Environmental Sustainability, 6*, 22–27.

Nandwa, S. M., & Bekunda, M. A. (1998). Research on nutrient flows and balances in east and southern Africa: state-of-the-art. *Agriculture, Ecosystems and Environment, 71*, 5–18.

Newton, A. C., Begg, G. S., & Swanston, J. S. (2009). Deployment of diversity for enhanced crop function. *Annals of Applied Biology, 154*, 309–322.

Nyagumbo, I., & Bationo, A. (2011). Exploring crop yield benefits of integrated water and nutrient management technologies in the desert margins of Africa: experiences from semi-arid Zimbabwe. In A. Bationo, B. Waswa, J. M. Okeyo, F. Maina, & J. M. Kihara (Eds.), *Innovations as key to the green revolution in Africa* (pp. 759–772). Netherlands: Springer.

Nyende, P., & Delve, R. J. (2004). Farmer participatory evaluation of legume cover crop and biomass transfer technologies for soil fertility improvement using farmer criteria, preference ranking and logit regression analysis. *Experimental Agriculture, 40*, 77–88.

Okalebo, J. R., Othieno, C. O., Woomer, P. L., Karanja, N. K., Semoka, J. R. M., Bekunda, M. A., Mugendi, D. N., Muasya, R. M., Bationo, A., & Mukhwana, E. J. (2006). Available technologies to replenish soil fertility in East Africa. *Nutrient Cycling in Agroecosystems, 76*, 153–170.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G., & Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems & Environment, 83*, 27–42.

Pauw, K., Thurlow, J., Bachu, M., & Van Seventer, D. E. (2011). The economic costs of extreme weather events: a hydrometeorological CGE analysis for Malawi. *Environment and Development Economics, 16*, 177–198.

Power, A. G. (2010). Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences, 365*, 2959–2971.

Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany, 114*(8), 1571–1596.

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability, 9*, 5–24.

Pugalenthi, M., Vadivel, V., & Siddhuraju, P. (2005). Alternative food/feed perspectives of an underutilized legume *Mucuna pruriens var. utilis* – a review. *Plant Foods for Human Nutrition, 60*, 201–218.

Reynolds, T. W., Waddington, S. R., Anderson, C. L., Chew, A., True, Z., & Cullen, A. (2015). Environmental impacts and constraints associated with the production of major food crops in sub-Saharan Africa and South Asia. *Food Security, 7*(4), 795–822.

Rusinamhodzi, L., Corbeels, M., van Wijk, M. T., Rufino, M. C., Nyamangara, J., & Giller, K. E. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development, 31*, 657–673.

Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science, 295*, 2019–2020.

Schlecht, E., Buerkert, A., Tielkes, E., & Bationo, A. (2006). A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems, 76*, 109–136.

Shennan, C. (2008). Biotic interactions, ecological knowledge and agriculture. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences, 363*, 717–739.

Shiferaw, B., Prasanna, B. M., Hellin, J., & Bänziger, M. (2011). Crops that feed the world. 6. Past successes and future challenges to the role played by maize in global food security. *Food Security, 3*(3), 307–327.

Shumba, E. M., Waddington, S. R., & Rukuni, M. (1992). Tine tillage, with atrazine weed control, to permit earlier planting of maize by smallholder farmers in Zimbabwe. *Experimental Agriculture, 28*, 443–452.

Smith, L., Alderman, H., & Aduayom, D. (2006). *Food insecurity in sub-Saharan Africa: new estimates from household expenditure surveys*. Washington DC: International Food Policy Research Institute.

Smith, R. G., Gareau, T. P., Mortensen, D. A., Curran, W. S., & Barbercheck, M. E. (2011). Assessing and visualizing agricultural management practices: a multivariable hands-on approach for education and extension. *Weed Technology, 25*(4), 680–687.

Snapp, S. S. (1998). Soil nutrient status of smallholder farms in Malawi. *Communications in Soil Science and Plant Analysis, 29*, 2571–2588.

Snapp, S. S., & Silim, S. N. (2002). Farmer preferences and legume intensification for low nutrient environments. *Plant and Soil, 245*, 181–192.

Snapp, S. S., Mafongoya, P. L., & Waddington, S. (1998). Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agriculture, Ecosystems and Environment, 71*, 185–200.

Snapp, S., Kanyama-Phiri, G., Kamanga, B., Gilbert, R., & Wellard, K. (2002a). Farmer and researcher partnerships in Malawi: developing soil fertility technologies for the near-term and far-term. *Experimental Agriculture, 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? *Agriculture, Ecosystems and Environment, 91*, 159–174.

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. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 20840–20845.

Stroosnijder, L. (2007). Rainfall and Land Degradation. In Climate and land degradation. Berlin: Springer Berlin Heidelberg, pp. 167–195. Available at: http://link.springer.com/10.1007/978-3-540-72438-4_9.

Thierfelder, C., & Wall, P. C. (2009). Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research, 105*(2), 217–227.

Thierfelder, C., & Wall, P. C. (2012). Effects of conservation agriculture on soil quality and productivity in contrasting agro-ecological environments of Zimbabwe. *Soil Use Management, 28*, 209–220.

Thierfelder, C., Cheesman, S., & Rusinamhodzi, L. (2012). A comparative analysis of conservation agriculture systems: benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Research, 137*, 237–250.

Thierfelder, C., Chisui, J. L., Gama, M., Cheesman, S., Jere, Z. D., Bunderson, W. T., Eash, N. S., & Rusinamhodzi, L. (2013a). Maize-based conservation agriculture systems in Malawi: long-term trends in productivity. *Field Crops Research, 142*, 47–57.

Thierfelder, C., Mwila, M., & Rusinamhodzi, L. (2013b). Conservation agriculture in eastern and southern provinces of Zambia: long-term effects on soil quality and maize productivity. *Soil Tillage Research, 126*, 246–258.

Tittonell, P., Vanlauwe, B., Corbeels, M., & Giller, K. E. (2008). Yield gaps, nutrient use efficiencies and response to fertilizers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil, 313*, 19–37.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze, N., & Mahposa, P. (2010). Micro-dosing as a pathway to Africa's green revolution: evidence from broad-scale on-farm trials. *Nutrient Cycling in Agroecosystems, 88*, 3–15.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., & Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil, 339*, 35–50.

Vanlauwe, B., Wendt, J., Giller, K. E., Corbeels, M., Gerard, B., & Nolte, C. (2014). A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. *Field Crops Research, 155*, 10–13.

Versteeg, M. N., Amadji, F., Eteka, A., Gogan, A., & Koudokpon, V. (1998). Farmers' adoptability of mucuna fallowing and agroforestry technologies in the coastal savanna of Benin. *Agricultural Systems, 56*, 269–287.

Vissoh, P., Manyong, V. M., Carsky, J. R., Osei-Bonsu, P., & Galiba, M. (1998). Experiences with macuna in West Africa. In D. Buckles, A. Eteka, O. Osiname, M. Galiba, & G. Galiano (Eds.), *Cover crops in West Africa contributing to sustainable agriculture*. Ottawa: IDRC IITA, Ibadan; SG2000, Cotonou.

Waddington, S.R., Sakala, W.D., & Mekuria, M. (2004). Progress in lifting soil fertility in Southern Africa. *Proceedings of the 4th International Crop Science Congress, 26 September - 1 October, 2004*. ICSC, Brisbane, Australia. http://www.cropscience.org.au/icsc2004.

Waddington, S. R., Mekuria, M., Siziba, S., & Karigwindi, J. (2007a). Long-term yield sustainability and financial returns from grain legume-maize intercrops on a sandy soil in subhumid north Central Zimbabwe. *Experimental Agriculture, 43*(4), 489–503.

Waddington, S. R., Karigwindi, J., & Chifamba, J. (2007b). The sustainability of a groundnut plus maize rotation over 12 years on smallholder farms in the sub-humid zone of Zimbabwe. *African Journal of Agricultural Research, 2*, 342–348.

Waddington, S. R., Li, X., Dixon, J., Hyman, G., & de Vicente, M. C. (2010). Getting the focus right: production constraints for six major food crops in Asian and African farming systems. *Food Security, 2*(1), 27–48.

Wopereis, M. C. S., Tamélokpo, A., Ezui, K., Gnakpénou, D., Fofana, B., & Breman, H. (2006). Mineral fertilizer management of maize on farmer fields differing in organic inputs in the west African savanna. *Field Crops Research, 96*(2), 355–362.

Zingore, S., Murwira, H. K., Delve, R. J., & Giller, K. E. (2007). Soil type, management history and current resource allocation: three dimensions regulating variability in crop productivity on African smallholder farms. *Field Crops Research, 101*, 296–305.

Professor Sieg Snapp is a soils and cropping systems ecologist at Michigan State University and Associate Director of the Center for Global Change and Earth Observations. She has edited two books and published more than a 100 journal articles and extension bulletins on sustainable intensification, agricultural systems, and participatory action research. Her research interests include international agricultural system design for a changing climate and understanding factors driving land management in tropical Africa and processes that can be harnessed for sustainable production. She has pioneered the development of multipurpose crops for food and environmental security, including the first agronomic reports on perennial wheat and perennial pigeonpea. Dr. Snapp has extensive experience in the use of participatory action research and extension, and a commitment to co-learning. She is possibly best known for being the 'mother' of the mother and baby trial design, as a means to support participatory research, communication and innovation.

Klaus Droppelmann studied tropical plant production at University of Hohenheim in Germany graduating in 1993. For his PhD he moved to the faculty of Geooecology at the University of Bayreuth. In his research work he specialised in water-harvesting technologies for annual cereal and agro-forestry systems in Israel and Kenya, respectively. After a few years as Post-doctoral researcher at the Wyler Department for Desert Agriculture in Israel, he moved on to join the German development co-operation in Zambia in the year 2001. There he first focused on institutional capacity strengthening of decentralised agricultural stakeholder organisations and advised a microcredit fund. From 2004 to 2008 he worked at a national consultation platform in Zambia's agricultural sector where he gained a deep understanding of institutional relationships and policy processes around agricultural development in southern African. In late 2008 he joined IFRPI to assist in the roll-out of its country program in Malawi and subsequently became its acting team leader. Since 2013 Klaus is based in Johannesburg, South Africa working as an independent consultant and process facilitator. His main research interests revolve around water efficient smallholder farming systems, technology uptake and agricultural policy processes.

Stephen Waddington is an agronomist, with a PhD on the yield physiology of barley, obtained from the University of Reading, UK in 1983. He has around 30 years of experience with agricultural research and development in southern and eastern Africa, south Asia and Mexico, much of it while working with CIMMYT. His main research interests have involved smallholder farming systems and participatory research, maize and wheat crop production agronomy and seed systems, soil fertility management for maize-legume cropping systems, water management, crop-livestock interactions, environmental impacts of cropping systems, and cereal yield physiology. He has also been closely involved with capacity building and networking initiatives in several of these areas, including 10 years as coordinator of the Soil Fertility Network for Southern Africa, funded by the Rockefeller Foundation. Stephen is currently an independent agricultural consultant and is based in Mexico. Recent work has included maize advisor to Katalyst-Swisscontact in Bangladesh, research on crop-environment interactions with the University of Washington for the Bill and Melinda Gates Foundation, and support to the Michigan State University-Africa Rising project in Malawi.