Agronomy for Sustainable Development (2021) 41: 16
https://doi.org/10.1007/s13593-021-00673-4

REVIEW ARTICLE

Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review

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Accepted: 26 January 2021 / Published online: 23 February 2021

Abstract

Africa's need to double food production and feed the burgeoning human population, without compromising its natural resource base, has raised the momentum for sustainable agricultural intensification on the continent. Many studies describe agronomic practices that can increase productivity on existing agricultural land without damaging the environment and without increasing the agricultural carbon footprint. However, there is limited information on specific practices with the greatest potential to contribute to sustainable intensification on smallholder farms in sub-Saharan Africa, while simultaneously keeping the carbon footprint low. The objectives of this review were to (1) identify good agronomic practices with potential for contributing to sustainable intensification across sub-Saharan Africa, (2) synthesize available information on benefits and synergies from these technologies, and (3) discuss bottlenecks in their adoption in order to obtain insights that inform the formulation of supportive policies. Agroforestry, cereal-legume intercropping, conservation agriculture, doubled-up legume cropping, fertilizer micro-dosing, planting basins, and push-pull technology were identified as key agronomic innovations widely promoted in sub-Saharan Africa. We show that these innovations can build synergies and increase resource use efficiency while reducing agricultural carbon footprint. We outline the benefits, trade-offs, and limitations of these practices and discuss their potential role in strengthening food sovereignty and climate change adaptation and mitigation.

Keywords Agroforestry · Intercropping · Micro-dosing · Push-pull technology · Synergy · Trade-off

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1 Introduction

Sub-Saharan Africa (SSA) is characterized by low-input agriculture that leads to low yields. To offset the yield gap, the region depends on further land clearing and deforestation (Vanlauwe et al. 2014), which has led to rapid degradation of over 95 million hectares of land in SSA (Nkonya et al. 2016). In agricultural landscapes, poor farmers open up and over-crop marginal land because they lack alternative income sources or better farming technology. In terms of total economic value, the cost of land degradation is estimated at US$65 billion per year or about 7% of the total GDP of the SSA region (Nkonya et al. 2016). Clearing of forests for agriculture, loss of vegetative cover, and depletion of soil organic matter are recognized as the root causes of most soil degradation in SSA (FAO and ITPS 2015). Reversing these trends requires identifying new or existing agronomic innovations that can increase food production from the available land while reducing the carbon footprint from agriculture (Fig. 1). To reduce carbon footprint, land clearance rates for agricultural purposes will have to decrease and the necessary yield increases achieved through innovations on existing agricultural land. The challenge is that SSA farming is primarily based on smallholder systems where farmers produce for subsistence, with limited or no access to external inputs, or are marginalized from produce markets (AGRA 2017). While these low-input smallholder farming systems result in low greenhouse gas (GHG) emissions, they are also low-yielding.

There is growing interest in sustainable intensification, defined as producing more output from the same area of land while reducing the negative environmental impacts and, at the same time, increasing contributions to natural capital and the flow of environmental services (Pretty et al. 2011; Smith et al. 2017). Sustainable intensification is particularly crucial for SSA, a region projected to reach a population of 2.5 billion, or 21% of the total world population, by 2050 (United Nations 2017). Besides the growing population, rapid urbanization and rising consumer purchasing power are projected to increase food demand in the region (AGRA 2017). Climate change is another challenge that requires innovative ways of farming to mitigate crop losses associated with both long-term climatic changes and extreme weather events. To meet the projected doubling of food demand, 80% of the required increase in crop production in developing countries, including SSA, must come from improved varieties and agronomic practices, with only 20% coming from expanding arable land (Bruinsma 2009). Without innovative farming practices, the ~70% of the continent's population who are engaged in agriculture (AGRA 2017) will continue producing at below average world production levels, due to low soil fertility, water stress, crop pests and diseases, and climate change shocks (Calzadilla et al. 2009).

The dramatic increases in harvested area for the main food crops in SSA (Fig. 2a, c–f) show that 91–98% of the increase in maize (*Zea mays* L.), cassava (*Manihot esculenta* Crantz), beans (*Phaseolus vulgaris* L.), soybean (*Glycine max* (L.) Merr.), and pigeon pea (*Cajanus cajan* (L.) Huth) production have been achieved through an increase in area (FAO 2019). In comparison, only 2–8% derive from an increase in productivity. Yet, merely bringing more land into agriculture is neither viable nor sustainable for attaining food security (Vanlauwe et al. 2014). Many factors support these propositions, underscoring the need for increased adoption of agronomic innovations in SSA. First, much of the land that is ideal for farming is already being cultivated, and the remaining land that can potentially be brought to cultivation is marginal or under conserved natural ecosystems (Vanlauwe et al. 2014). Second, bringing more land into cultivation has no benefits, since the ability to produce food in SSA is limited by the demand for land from other human activities and the need to reduce GHG emissions from land clearance (AGRA 2017). Third, climate change, land degradation, and other consequences of unsustainable land management are expected to lower crop production in the region by approximately 1.6% by 2050 if no adaptation actions are taken (Calzadilla et al. 2009). This raises the need to address factors that limit production by fully exploiting appropriate genotype, management, and environment interactions that increase crop productivity and yields.

Despite the impressive gains in crop improvement in some countries, the average yield gains for some crops have remained static (Fig. 2a–f) or have declined in many areas (Bruinsma 2009; Grassini et al. 2013; Ray et al. 2013; Abate

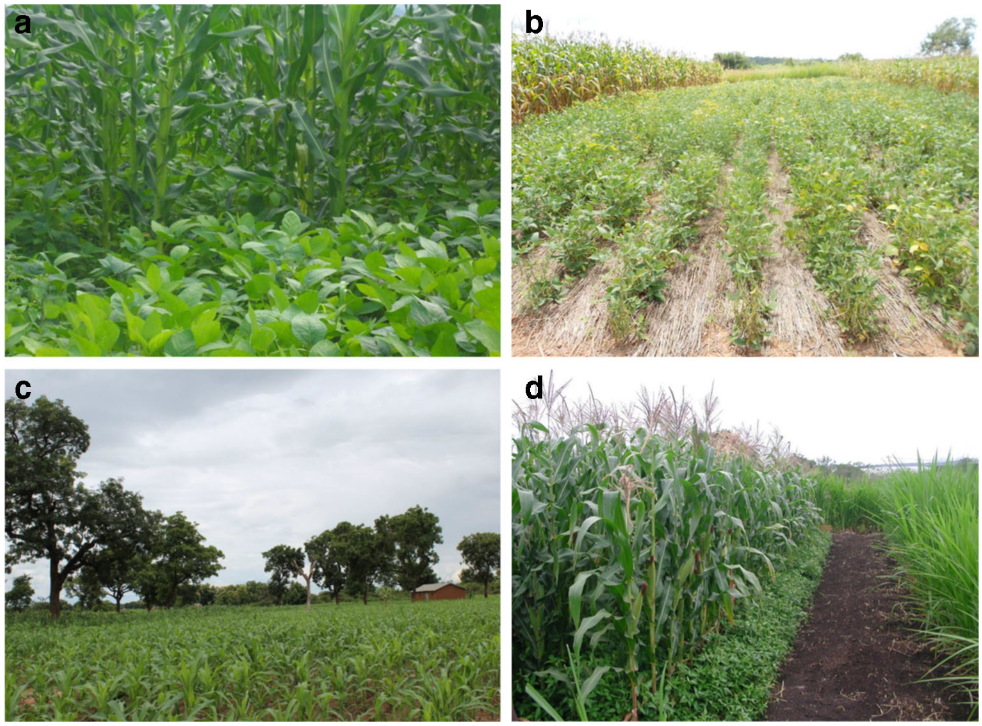

Fig. 1 Examples of innovations reported to contribute to sustainable food systems in sub-Saharan Africa. **a** Cereal-legume intercropping (maize-soybean intercrop in Rwanda). **b** Conservation agriculture (mulched soybean). **c** Agroforestry (parkland trees with maize in Burkina Faso). **d** Push-pull technology (maize intercropped with desmodium with Napier grass as a border crop in Kenya)

et al. 2017). For example, up to 214 improved maize varieties with yield potential >5 Mg ha^{-1} have been released in many SSA countries since the 1960s (Abate et al. 2017) (Fig. 3). However, maize yields in SSA have remained below 2 Mg ha^{-1} during the same period (Grassini et al. 2013) (Fig. 2a). These trends are particularly troubling in Kenya, Zambia, and Zimbabwe, where maize yields are decreasing by 0.2–7.6% per year (Ray et al. 2013) despite the large number of improved varieties released in these countries (Fig. 3b). Similar trends are evident for other crops despite significant crop variety improvements (Fig. 2). Improved varieties can only perform to their genetic potential when good agronomic practices (GAPs) are applied. In food-insecure regions, productivity gains from improved management are often far greater than those from improved genetics.

Good agronomic practices serve more than one purpose; they increase crop production and productivity through more efficient use of agricultural inputs while reducing emissions and losses. Benefits derived from a particular technology or management practice depend on execution and context of its application. Yet information on innovations that have the most significant potential to contribute to sustainable intensification of farming in SSA is limited. This knowledge gap has hampered formulation of evidence-based policies supporting scaling up of GAPs and, consequently, their broad adoption in the region. The objectives of this narrative review were therefore to (1) identify GAPs with the potential to contribute significantly to sustainable intensification across SSA, (2) provide a synthesis of their ability to provide multiple benefits and synergies, and (3) discuss bottlenecks in their adoption. These three objectives were intended to provide insights that can inform the formulation of supportive policies.

2 Methods

2.1 Scope, search strategy, and selection of studies

We performed a critical review of the literature to identify GAPs widely promoted as entry points for sustainable intensification of agriculture in SSA. The review process involved an online search of material indexed in bibliographic databases and other sources (Fig. 4). First, we identified a list of sustainability indicators in agricultural production, focusing on two sustainable intensification domains, productivity and environment. Among the indicators for sustainable intensification, crop yield is the most common productivity indicator (Smith et al. 2017). We focused on crop yield because increasing crop productivity is a fundamental characteristic of intensification (Musumba et al. 2017). We also included soil quality, input (nutrient, water) use efficiency, pest control, and GHG emissions as indicators of sustainable intensification. Scientific evidence shows that poor soils, input use inefficiencies, and pests are major constraints to productivity, while the continuing rise in GHG emissions is responsible for climate change, negatively impacting agricultural production.

We applied search strings with the following keywords to retrieve publications indexed in Web of Science and Scopus: TS=((“crop yield” OR “soil quality” OR “soil fertility” OR “soil moisture” OR “water use efficiency” OR “nutrient use

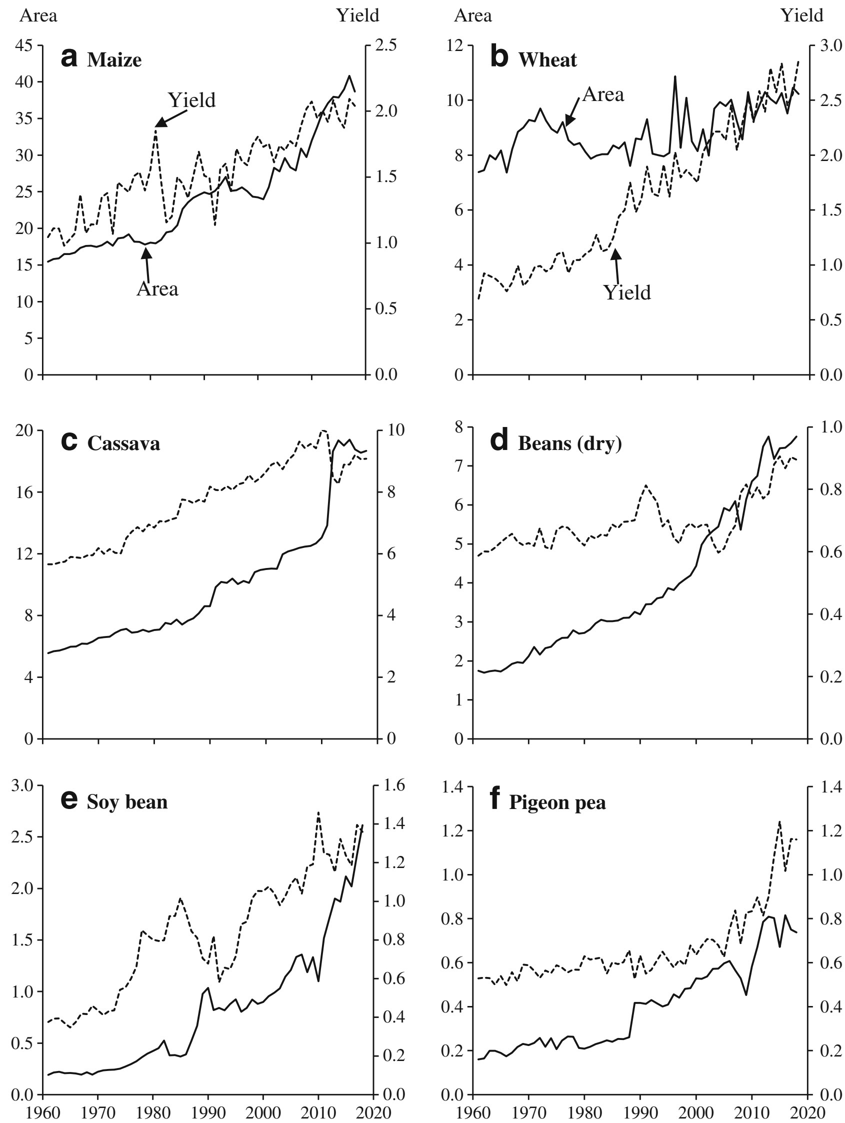

Fig. 2 Comparison of trends in area harvested (million ha) and yield (Mg ha^{-1}) of crops for which significant progress has been made in breeding in Africa (1960–2017). **a** Maize (*Zea mays* L.). **b** Wheat (*Triticum aestivum* L.). **c** Cassava (*Manihot esculenta* L.). **d** Common beans (*Phaseolus vulgaris* L.). **e** Soybean (*Glycine max* L.). **f** Pigeon pea (*Cajanus cajan* L.). All values calculated from FAOSTAT data (2019)

efficiency" OR "pest" OR "disease" OR "weed" OR "greenhouse gas emission") AND ("sustainable intensification") AND ("sub-Saharan Africa")). The search was conducted for publications in the English language covering the period 1997–2020. This covered the time when Pretty (1997) first coined the term "sustainable intensification" and when the literature on sustainable intensification increased (Weltin et al. 2018). We complemented electronic searches on bibliographic databases by checking references of the papers retrieved from Google Scholar searches. The search yielded a total of 577 peer-reviewed publications (Fig. 4). We assessed the relevance of publications retrieved by reviewing the title and abstract and finally conducting full-text appraisals. To be included in the synthesis, publications had to report a specific agronomic practice or a group of practices on experiments conducted in SSA and the corresponding impact on the indicators identified in Table 1.

2.2 Evaluation of agronomic practices

From 87 publications meeting the selection criteria, we identified seven agronomic practices that improve either one or a combination of factors contributing to sustainable intensification of crop production systems. Whenever available, information on the land area covered by the agronomic practices or the number of farmers that use the practices was retrieved. A vote-count approach was used to determine the impact of agronomic practices on five major factors (crop yield, soil quality, input use efficiency, pest control, GHG emissions) contributing to sustainable intensification of agricultural production systems. Each study was categorised as having a positive, negative or neutral effect. A positive effect suggests an increase or improvement in a given indicator, a negative effect suggests a decrease, and a neutral outcome suggests no significant effect or a context-specific effect. Reductions in GHG

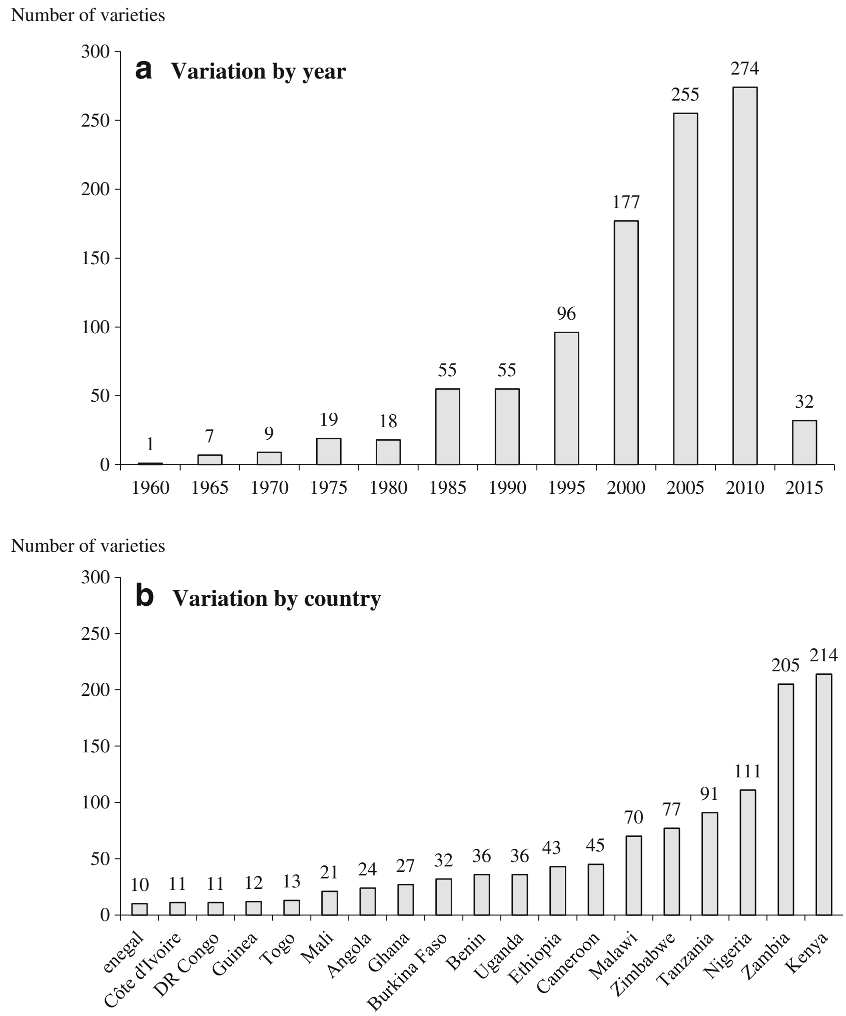

Fig. 3 Number of maize varieties released between 1960 and 2013 in various countries. **a** Variation by year. **b** Variation by country

emissions were considered a positive effect. Results from vote counts were augmented by an expert knowledge-based assessment of the importance of agronomic practices identified for sustainable intensification. The assessment used the advantages and limitations reported to assign positive and/or negative contributions to sustainable intensification.

We obtained total emission data for the various sectors, i.e., energy, agriculture, industrial processes, and products and waste, from FAOSTAT for the period 1997–2017 (FAO 2019), to calculate the contribution of agriculture to total GHG emissions (Fig. 5). The total GHG emission data provide a complete picture of the contribution of agriculture to

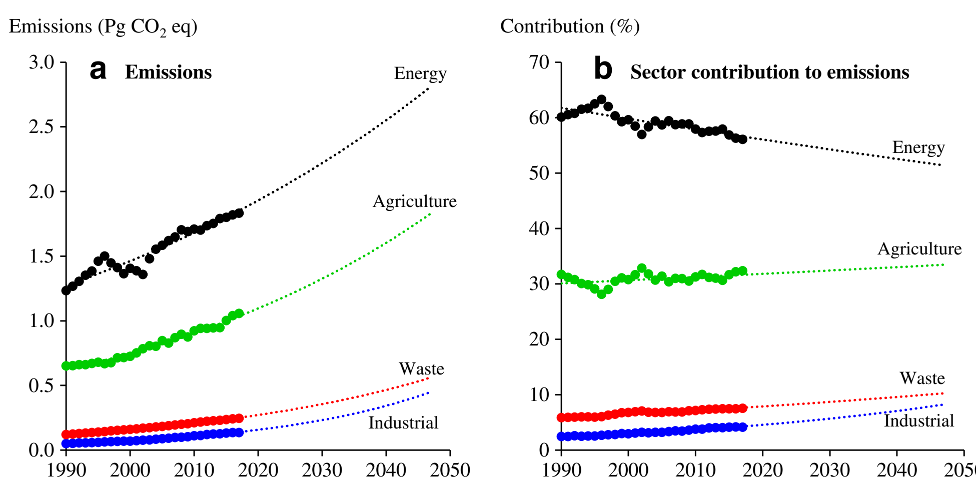

Fig. 4 Comparison of trends in emissions from agriculture with other sectors. **a** Amount in carbon dioxide (CO_2) equivalents. **b** Percentage contribution of each sector to total emissions. All values calculated from FAOSTAT data (2019) using the IPCC fifth assessment report (IPCC 2014). Solid lines represent actual values 1990–2017, while broken lines are forecast values for 2050

Table 1 Estimated area (in million hectares) under the various interventions or estimated number of farmers practicing the interventions and their impacts on crop yields, soil quality, input use efficiency, pest control, and greenhouse gas emissions. The values indicate the number of studies reporting an impact of the practice on the indicators. +/− means that the practice had a neutral impact or the impact was context-specific according to the study

Agronomic practice	Approximate area/number of farmers	Effect	Indicator					References
			Crop yield	Soil quality	Input use efficiency	Pest control	GHG emissions	
Cereal-legume intercropping	NA	Increase (+)	18	3	3	2	1	(Drinkwater et al. 1998; Rao and Mathuva 2000; Snapp et al. 2002a, p. 2002b, p. 2018a, p. 2018b; Myaka et al. 2006; Waddington et al. 2007; Kimaro et al. 2009; Rusinamhodzi et al. 2012, 2020; Ojiem et al. 2014; Arslan et al. 2015; Falconnier et al. 2016; Droppelmann et al. 2017; Franke et al. 2018; van Vugt et al. 2018; Chimonyo et al. 2019; Demissie et al. 2019; Kermah et al. 2019; Kiwia et al. 2019; Diatta et al. 2020; Madembo et al. 2020; Namatsheve et al. 2020; Nassary et al. 2020a, b; Mupangwa et al. 2021)
		Neutral (+/−)	6	1				
		Decrease (−)	2					
Doubled-up legume technology		Increase (+)	5	3				(Snapp et al. 2002a, p. 2002b, p. 2002; Chikowo et al. 2015, 2020; Smith et al. 2016)
		Neutral (+/−)		1				
		Decrease (−)						
Conservation agriculture (CA)	7.7*	Increase (+)	17	6	6	1	1	(Rusinamhodzi et al. 2011, 2012; Bayala et al. 2012; Arslan et al. 2015; Nyagumbo et al. 2015, 2016, 2020; Pittelkow et al. 2015a, b; TerAvest et al. 2015; Thierfelder et al. 2015, 2016, 2017; Micheni et al. 2016; Mupangwa et al. 2016, 2018, 2019, 2021; Droppelmann et al. 2017; Kafesu et al. 2018; Magombeyi et al. 2018; Mashavakure et al. 2018; Assefa et al. 2019; Belay et al. 2019; Corbeels et al. 2019; Komarek et al. 2019; Kihara et al. 2020; Mutuku et al. 2020; Yimam et al. 2020)
		Neutral (+/−)	8	2			1	
		Decrease (−)	1					
Agroforestry and cover cropping	113.8†	Increase (+)	4	7	4	2		(Kinama et al. 2007; Mutegi et al. 2008; Sileshi et al. 2008; Baudron et al. 2015; Pumariño et al. 2015; Kuyah et al. 2016, 2019; Droppelmann et al. 2017; Blaser et al. 2018; Magombeyi et al. 2018; Rahn et al. 2018; Sida et al. 2018, 2020; Wolka et al. 2018; Kuria et al. 2019; Muchane et al. 2020)
		Neutral (+/−)	3	2	2			
		Decrease (−)	3			1		
Planting pits		Increase (+)	10	5	5	2		(Roose et al. 1999; Malley et al. 2004; Fatondji et al. 2006; Amede et al. 2011; Zougmoré et al. 2014; Thierfelder et al. 2015; Kafesu et al. 2018; Magombeyi et al. 2018; Mashavakure et al. 2018; Dahlin and Rusinamhodzi 2019; Chilagane et al. 2020; Ibrahim and Fatondji 2020; Muchai et al. 2020)
		Neutral (+/−)			1			
		Decrease (−)						
Push-pull	70,000‡	Increase (+)	10			10		(Khan et al. 2002, 2006, 2009, 2014; Midega et al. 2015, 2017, 2018; Kebede et al. 2018; D'Annolfo et al. 2020; Ndayisaba et al. 2020)
		Neutral (+/−)						
		Decrease (−)						
Fertilizer and manure micro-dosing		Increase (+)	22	2				(Aune et al. 2007; Ncube et al. 2007; Tabo et al. 2007; Hayashi et al. 2008; Twomlow et al. 2010; Bielders and Gérard 2015; Ibrahim et al. 2015, 2016a, b; Adams et al. 2016; Okebalama et al. 2016; Tonitto and Ricker-Gilbert 2016; Tovihoudji et al. 2017, 2019; Vandamme et al. 2018; Coulibaly et al. 2019; De Bauw et al. 2019; Saidia et al. 2019; Nourou et al. 2020; Ouedraogo et al. 2020)
		Neutral (+/−)		1				
		Decrease (−)		2				

*Conservation agriculture is estimated to be below 1% of agricultural land in sub-Saharan Africa

† Area of agricultural land with greater than 10% tree cover (1,137,864 km^2) in 2010 (Zomer et al. 2014)

‡ Number of farmers that have adopted the push-pull technology. As of 2014, an estimated 68,800 smallholder farmers in Kenya, Uganda, Tanzani, and Ethiopia had adopted push-pull technology (Khan et al. 2014)

atmospheric carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentrations, which are associated with crop and livestock production and related management activities (FAO 2019). We summarised values computed using the IPCC fifth assessment report (IPCC 2014) and expressed them in Pg (10^{15} g) carbon dioxide equivalents (CO_2 eq.). We also obtained data from FAOSTAT for the period 1997–2017 (FAO 2019) to show trends in the harvested area and yield of maize, wheat (*Triticum aestivum* L.), cassava, common bean, soybean, and pigeon pea. These were selected because they are the main crops that have received significant investments for breeding and agronomic research in SSA.

3 Potential agronomic practices

We identified seven agronomic practices that can potentially contribute, or are already contributing, to sustainable intensification in SSA (Table 1). In terms of land area or the number of farmers that use the practices, information was only available for four of the seven practices. The other three practices showed lower importance at the regional scale. All the practices showed several positive impacts on sustainable intensification indicators, with a few negative impacts. Below, we provide detailed reviews of the seven agronomic practices and discuss the reasons for their adoption or non-adoption by smallholder farmers.

3.1 Cereal-legume intercropping

Intercropping cereals with legumes is an old tradition that has been practised by most smallholder farmers throughout much of SSA and has been identified as one of the sustainable intensification strategies in smallholder agriculture in SSA (Snapp et al. 2002b, 2018b; Kiwia et al. 2019). A review of the potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of SSA has been carried out previously (Kiwia et al. 2019). However, accurate estimates of the area under intercropping are still not available. Typically, cereals constitute the main crop. Common cereals in SSA include maize, sorghum (*Sorghum bicolor* L. Moench.), and finger millet (*Eleusine coracana* L. Gaertn.). Legumes are generally the companion crop and can be selected to produce food, e.g., pigeon pea, cowpea (*Vigna unguiculata* L. Walp.), common bean or groundnut (*Arachis hypogea* L.), and/or fodder, e.g., *Stylosanthes* spp., *Trifolium* spp., and *Vicia* spp. Cereal-legume intercropping is common in Southern and East Africa, where maize is traditionally intercropped with common bean, pigeon pea, cowpea, or soybean. Compared with sole cropping (monocultures), cereal-legume intercropping increased crop yield in 18 of the studies reviewed (n=87), reduced yield in six studies, and did not have a significant effect in two studies (Table 1). In most studies, the increased yield was attributed to improved soil fertility through biological nitrogen fixation. Under certain situations, intercropping

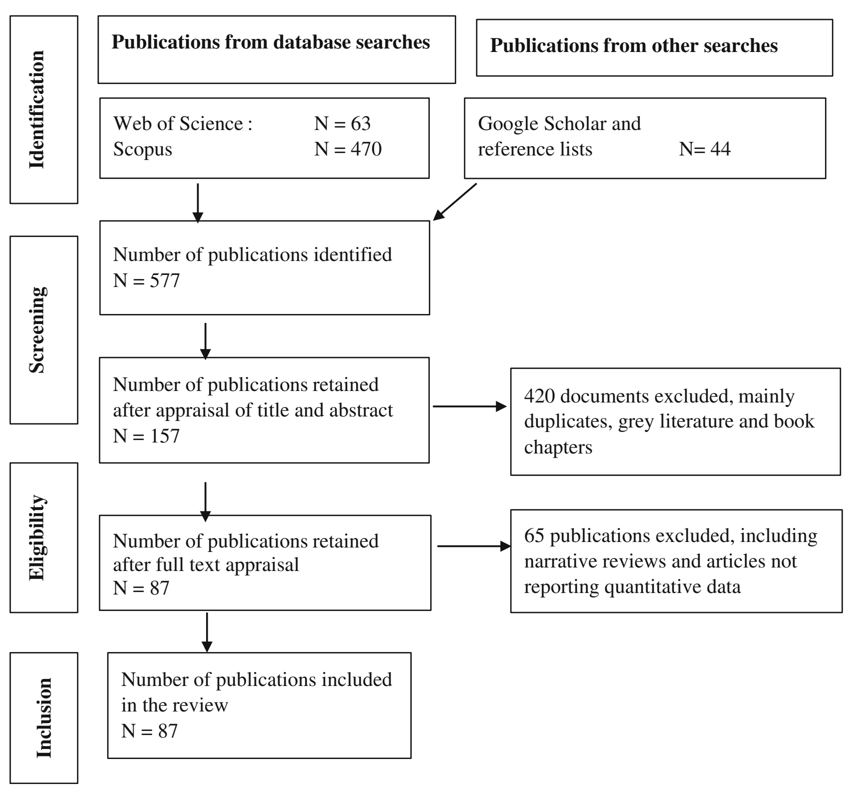

Fig. 5 Flow diagram of the review process showing the number of studies returned by the search and studies included or excluded at each stage

contributed to reducing yield losses by controlling weeds or regulating pest or disease populations (Rusinamhodzi et al. 2012; Franke et al. 2018). Studies reporting effects of intercropping on soil quality, improved input use efficiency, pest control, and GHG emissions were few (Table 1).

Pigeon pea is one of the legumes shown to have high potential for intercropping with cereals in Southern and East Africa, where it plays a vital role in household nutrition and income generation (Snapp et al. 2002a; Kiwia et al. 2019). Unlike most legumes, pigeon pea is well adapted to semi-arid and arid regions, where it is grown in association with maize, sorghum or millet (Odeny 2007). Growing pigeon pea as an intercrop with cereals diversifies the production system and reduces risks associated with monocultures, such as high use of fertilizers, high pest pressure, loss of biodiversity, degradation of soil quality, and environmental pollution (Snapp et al. 2010; Kiwia et al. 2019). In Burkina Faso, Malawi, and Mozambique, growing maize with pigeon pea has been found to reduce crop failure risk even when fertilizer is not applied (Snapp et al. 2010; Rusinamhodzi et al. 2012; Kiwia et al. 2019). Pigeon pea harvested during the dry season has been found to represent a food source that helps bridge hunger periods in Tanzania and Malawi (Myaka et al. 2006; Kimaro et al. 2009).

Intercropping pigeon pea with maize has been shown to produce higher yields per unit area. Maize intercropped with pigeon pea can achieve yields comparable with, or higher than, those obtained in sole maize cropping (Rao and Mathuva 2000; Myaka et al. 2006) due to increased soil fertility over time (Snapp et al. 2002b; Rusinamhodzi et al. 2012; Kiwia et al. 2019). In semi-arid Kenya (the Machakos area), maize-pigeon pea intercropping produced 24% higher maize yields (2.67 Mg ha^{-1}) than the mono-cropped maize (2.46 Mg ha^{-1}) (Rao and Mathuva 2000). In Tanzania, the yield of unfertilized maize intercropped with pigeon pea was similar to the yield of a moderately fertilized maize crop (Myaka et al. 2006). Across Malawi, the average grain yield of maize and pigeon pea over two years in on-farm trials was higher than in monoculture systems (Snapp et al. 2002b). Farmers who grow pigeon pea can also benefit from fodder for livestock and firewood for household energy needs.

The primary trade-off in cereal-legume intercropping is competition for growth factors that negatively affect crop yield (Waddington et al. 2007; Kimaro et al. 2009; Kiwia et al. 2019). Legumes also face competition for land, labor, and cash with other crops and farm activities (Snapp et al. 2002b). In Tanzania, intercropping maize-pigeon pea was found to enhance maize yield over sole maize only when fertilized, suggesting possible competition for nutrients (Kimaro et al. 2009). In a long-term experiment in north-central Zimbabwe, Waddington et al. (2007) found that maize was suppressed when intercropped with pigeon pea during some growing seasons. Some legumes contribute small amounts of nitrogen to the next crop, since large amounts of the nitrogen fixed by the legume are removed when the grain and residues are harvested and removed from the field. However, longer season legumes (e.g., pigeon pea) can increase the amount of fixed nitrogen. Where intercropping is likely to suppress yields or increase nutrient mining, applying the recommended doses of nitrogen and phosphorus fertilizers or manure has been demonstrated to increase yields and net incomes (Kiwia et al. 2019).

3.2 Doubled-up legume technology

Doubled-up legume technology involves intercropping two legumes with complementary growth habits and plant architecture in rotation with a cereal (Chikowo et al. 2015; Smith et al. 2016). Smallholder farmers widely use this practice in Malawi, where mixtures of pigeon pea and soybean or groundnut or cowpea are grown (Rogé et al. 2016; Smith et al. 2016). The practice takes advantage of synergies that occur when crops in the mixtures place significant demands on resources at different times or exploit resources at different depths within the soil profile. In principle, the two legumes are planted as they would be in a sole crop. When pigeon pea and groundnuts are planted simultaneously, the pigeon pea plants grow slowly for the first two months, allowing groundnut plants to grow with little competition for water, nutrients, and sunlight (Chikowo et al. 2015, 2020). Pigeon pea then starts growing fast when the groundnut is approaching maturity and continues to grow as a sole crop until it is harvested (Chikowo et al. 2015, 2020).

Doubled-up legumes offer multiple benefits in cropping systems compared with monoculture practices (Snapp et al. 2010; Chikowo et al. 2020). Five of the studies reviewed indicated that doubled legume technology increases crop yield. Under good rainfall, the technology raises land productivity, allowing farmers to benefit from two-grain harvests. Evidence of greater yields from legume-legume systems is documented for countrywide trials conducted in Malawi. Across different environments, sole groundnut and pigeon pea produced 1.4 and 0.9 Mg ha^{-1}, respectively, compared with 1.2 and 0.5 Mg ha^{-1} in the doubled-up system (Chikowo et al. 2015). These yield levels suggest that pigeon pea intercropped with groundnut can produce yields close to sole-cropped pigeon pea. Doubled-up legumes also increased the yield of maize grown in the subsequent seasons. After 2 years of pigeon pea/groundnut intercrop, maize yield increased by 45% across various Malawian environments (Snapp et al. 2002a, b). Using data from 26 growing seasons, Smith et al. (2016) found that maize grain yields in doubled-up legume rotations and maize-legume rotations were comparable and surpassed yields in a maize/pigeon pea intercrop and sole-cropped maize where similar fertilizer inputs were applied. Yields of maize grown after the intercrop were higher than yields in conventional cereal-legume intercropping (Smith et al. 2016). Trials in eastern Zambia also showed the potential of doubled-up legumes, with better spatial arrangement of groundnut in pigeon pea recommended for increasing the yield of maize planted after the legumes (Thierfelder et al. 2017).

Doubled-up legumes have been shown to improve soil fertility, as both crops contribute above and below biomass and fix nitrogen through biological fixation (Smith et al. 2016). Improved soil fertility results from large amounts of organic mulch from pigeon pea leaves that fall to the ground as the crop matures. Residues produced by legume-based systems in on-farm trials in Malawi contained about 50 kg N ha^{-1} $year^{-1}$, twice the amount of residues from sole-cropped maize (Snapp et al. 2002b). As the other legume (soybean or groundnuts) intercropped with pigeon peas also fixes nitrogen, the doubled-up legume intercropping system results in 20–50% more biological nitrogen fixation inputs compared with sole legume cropping (Chikowo et al. 2020). Pigeon pea also improves soil structure through its extensive root system and the large amount of litter produced adds organic matter to the soil. Exudates from the roots have been shown to enhance phosphorus cycling efficiency in agricultural systems by unlocking fixed phosphorus (Nziguheba et al. 2016). By improving soil fertility, doubled-up legume intercropping reduces the fertilizer requirements for cereal crops grown in rotation by about 50%, with minimum yield reduction (Chikowo et al. 2015; Rogé et al. 2016). Experiments in Malawi and Zambia have shown that maize grown in rotations and at 50% of the recommended nitrogen fertilizer produces yields comparable with maize receiving full fertilization (Chikowo et al. 2020).

Doubled-up legume technology has some limitations in terms of productivity and adoption of the practice. For example, areas with water limitations experience lower benefits due to poor pigeon pea performance in the intercrop (Smith et al. 2016). Farmers who cannot plant on time or effectively manage weeds may also fail to benefit from the technology. It is only with good management that the doubled-up legume intercropping technology can increase cereal productivity in crop sequences. As reported in a study conducted in Malawi, major bottlenecks to adopting doubled-up legume technology include the high cost of certified seeds, challenges with seed supply systems, high labor requirements, and limited access to lucrative markets (Kamanga et al. 2014).

3.3 Conservation agriculture

Conservation agriculture (CA) is practised on over 7.7 million hectares across Southern, East, and West Africa (Table 1). Conservation agriculture has three pillars: minimum soil discturbance, permanent soil cover with crop residues or live mulches (e.g., Fig. 1b), crop rotaion and intercroping (Lipper et al. 2014). All the three pillars potentially contribute to reducing GHG emissions and increasing sequestration of carbon in the soil. Continuous improvements in farming practices have given rise to innovative variants of CA (Giller et al. 2009).

The impact of CA on crop yield appears to be context-specific. Seventeen of the studies reviewed evaluating crop yield under CA reported positive effects and eight reported nonsignificant effects, while one study reported a decrease in crop yield. Recent meta-analyses show that CA increases crop yield and yield stability in drylands (Rusinamhodzi et al. 2011; Pittelkow et al. 2015a, b). For example, in drylands of West Africa (Burkina Faso, Mali, Niger and Senegal), variants of CA (e.g., parkland trees associated with crops, coppicing trees, green manure, mulching, crop rotation and intercropping, and traditional soil/water conservation) can improve cereal yields by between 0.14 and 0.24 Mg ha^{-1}, depending on tree species (Bayala et al. 2012). Long-term experiments in the drylands of Ethiopia and Southern Africa (Malawi, Mozambique, Zambia, and Zimbabwe) have also demonstrated that CA can increase grain yield relative to conventional agriculture (Thierfelder et al. 2015; Liben et al. 2018). Yield benefits become apparent 2–5 years after adoption, when farmers have become more experienced in performing CA practices (Thierfelder et al. 2015). Yield benefits are attributed to soil fertility improvements through biological nitrogen fixation and increased retention of soil moisture. There are also context-specific benefits of CA, such as erosion control, biodiversity increase, weed suppression, carbon sequestration, and reversal of soil degradation processes that are common in conventional crop production systems (Hobbs et al. 2008).

Challenges associated with CA include low yields (Giller et al. 2009), which can be around 10% lower than with conventional practices (Pittelkow et al. 2015b), increased labor requirements when herbicides are not used (Grabowski and Kerr 2014), lack of mulch due to low productivity or priority being given to the use of crop residues as livestock feed over mulch (Giller et al. 2009), and use of herbicides that might be detrimental to biodiversity. To overcome the low yields, Vanlauwe et al. (2014) proposed appropriate use of mineral fertilizer as the fourth principle of CA. However, as shown by both modeling and empirical studies, the yield benefits of CA are context-specific (Pittelkow et al. 2015a). For example, Rosenstock et al. (2014) found that CA is highly unlikely to generate yield benefits for farmers in Kenya and Tanzania, while Liben et al. (2018) showed that the short- and medium-term effects of CA in Ethiopia depend on initial soil properties. They concluded that improved water infiltration and crop yield could occur in the short term, but short-term yield increases are less likely with moderate soil fertility in humid areas (Liben et al. 2018). Other limitations associated with CA include the prevalence of weeds that are difficult to control without tillage (Lee and Thierfelder 2017). This weed challenge leads to increased reliance on herbicides. The high initial cost of specialist equipment and competition for crop residues between CA and livestock feeding is also a major limitation for CA.

Despite the potential of CA to deliver multiple positive impacts after a few years, CA adoption remains very low in SSA (<1%). This low adoption rate relates to the high variability in farmers' access to resources or specialist equipment. Giller et al. (2015) suggested that identifying and validating new technologies or practices which emphasise agronomy should become a "place-based" science. To enhance adoption, there is a need to apply general production ecology principles (theory) and agricultural development aspirations (direction) in specific local contexts and systems (Giller et al. 2015).

3.4 Agroforestry practices

Agroforestry, which is practised on 1.1 million km^2 of land in SSA (Table 1), integrates trees and crops, trees and pasture/livestock, or trees, crops, and pasture/livestock on the same area of land. A detailed definition of agroforestry and a general classification of agroforestry practices can be found in Sinclair (1999). The way in which the components of agroforestry are arranged and managed in the landscape constitutes agroforestry practice. Some agroforestry components/technologies (e.g., improved fallow/green manure) are called cover crops. Because of their deep roots and year-round vegetation cover, agricultural systems with trees and shrubs are inherently more sustainable and efficient in using plant nutrients than annual systems without trees.

The impacts of agroforestry on crop yield, soil quality, and pest control are context-specific and depend on the ecological conditions, the type of tree species, and the type of crop. In principle, agroforestry maintains high-productivity levels by harnessing ecosystem services provided by trees (Kuyah et al. 2016). Several meta-analyses have demonstrated that agroforestry practices in SSA improve crop yields (Sileshi et al. 2008), reduce pest problems (Pumariño et al. 2015), increase soil fertility, reduce runoff and soil loss, and increase infiltration rate and soil moisture content (Kuyah et al. 2019; Muchane et al. 2020). Different meta-analyses have demonstrated that crop yields are almost double in agroforestry compared with non-agroforestry systems, while control of runoff is fivefold higher, soil losses are 10-fold lower, and infiltration is about threefold higher in agroforestry compared with non-agroforestry systems (Kuyah et al. 2019; Muchane et al. 2020). However, depending on the context and management practice, trade-offs between trees and crops regarding access to nutrients, water, and light can also be experienced (Kuyah et al. 2016, 2019). Agroforestry generally does well in humid and sub-humid areas but may bring in trade-offs in areas where moisture is limiting (Kuyah et al. 2019).

The most effective agroforestry practices for soil and water conservation involve contour hedgerows with multipurpose leguminous trees and shrubs such as *Gliricidia sepium* (Jacq.) Kunth ex Walp., *Calliandra calothyrsus* Meissn., and *Leucaena trichandra* (Zucc.) Urban (Kinama et al. 2007; Mutegi et al. 2008). In the highlands of Central Kenya, contour hedgerow systems consisting of Calliandra and Napier grass (*Pennisetum purpureum* Schumach.) are commonly used to control erosion, restore fertility, and sometimes improve crop yields (Kinama et al. 2007; Mutegi et al. 2008). Farmers who practise agroforestry for soil and water conservation can transform previously degraded land into productive and high-yielding land (ibid.). Trees and shrubs in hedgerows may also be used as windbreaks and to control wind erosion in dry areas. However, trees tend to compete with crops when moisture is limiting or soils are infertile. Choosing the right tree, coupled with appropriate management such as pruning (trimming overgrown or unwanted branches or stems of a tree or a shrub), pollarding (cutting off the top and branches to encourage new growth at the top), or coppicing (cutting back a tree or shrub to ground level periodically, to stimulate growth), can minimize competition and eventual trade-offs (Kuyah et al. 2016).

Smallholder farmers who maintain a soil covering with trees or mulch from trees or cover crops increase the sustainability of their land. Cover crops and mulches have been used for decades in traditional farming systems in SSA. However, the practice has gained greater attention in recent years due to farming approaches such as CA with trees. Cover crops are planted to improve soil fertility, prevent soil erosion, and increase soil moisture content. Other documented benefits of cover crops in SSA include enhancing soil organic matter accumulation, weed suppression, and pest regulation (Daryanto et al. 2018). Perennial shrubs such as jack bean (*Canavalia ensiformis* (L.) DC.), sun hemp (*Crotalaria juncea* L.), and pigeon pea are preferred cover crop species because of their ability to fix nitrogen. Multipurpose leguminous tree species such as *Leucaena* spp., *Gliricidia* spp., *Sesbania* spp., and *Calliandra* spp. can also be lopped for mulch. Even though cover crops suitable for most farming systems and agroecological zones are available, they tend to compete with crops in areas where rainfall is limiting. Improved fallows are therefore preferred, since they utilise off-season resources. Improved fallows consist of leguminous trees and shrubs (e.g., *Tithonia diversifolia* (Hemsl.) A. Gray, *Crotalaria grahamiana*, *Sesbania* spp.) deliberately planted in rotation with cultivated crops to improve soil fertility through nutrient cycling and biological nitrogen fixation (Muchane et al. 2020). When properly managed, improved fallows can increase maize yields to about 6 Mg ha^{-1} (Partey et al. 2017) and conserve soil moisture for crop production (Sileshi et al. 2014).

Several previous studies suggest that the adoption of agroforestry has not matched its promise. In fact, in some cases, some agroforestry technologies have been abandoned because farmers did not obtain the intended benefits (Kiptot et al. 2007). Several factors constrain agroforestry adoption in SSA, with farmers' knowledge, attitudes, and perceptions playing a crucial role (Meijer et al. 2015). Other factors include high cost of establishment, reduced productivity due to competition for growth resources, favorable conditions that attract birds, primates and other pests and diseases, reduced area for crop production, unavailability of planting material, and delayed returns on investment. Planting multipurpose trees (e.g., fertilizer, fodder, timber, fruit trees) can help offset some of the trade-offs (Kuyah et al. 2020). A consideration when recommending agroforestry for smallholders is that it requires some investment in terms of inputs (seedlings) and time, since the benefits and co-benefits as products and services will not be experienced until after several seasons. Incentive schemes during the establishment year can be catalytic, as can including annual crops or forage species that yield crop and livestock products already in the first year.

3.5 Planting basins

Planting basins involve digging holes and planting crops to concentrate nutrients and water close to the plant. A unique form of planting basin known as *zaï* pits is common in the Sahel. *Zaï* pits are usually dug during the dry season and filled with one or two handfuls of dry dung, corresponding to 1–3 Mg dry organic matter ha^{-1} (Roose et al. 1999; Amede et al. 2011). Three to four seeds of sorghum or millet are sown per pit after the first rain.

Zaï pits have been used successfully in the Sahel for many years and are becoming more popular in East and Southern Africa. Similar technology with planting pits has been used in different regions, for example, *tassa* in Niger and Mali (Zougmoré et al. 2014), *ngoro* in Tanzania (Malley et al. 2004), and *katumani* pits in Kenya. Planting basins increase crop yield, improve soil quality and improve input use efficiency (Table 1). In Burkina Faso, *zaï* pits can increase yields by up to 1.5 Mg ha^{-1} in years when rainfall is good (Roose et al. 1999). Use of manure with *zaï* pits in Burkina Faso more than doubles grain yield relative to pits without manure (Fatondji et al. 2006). In the Ethiopian highlands, *zaï* pits combined with nitrogen inputs have been shown to increase potato yields by between 500 and 2000%, and yield of beans by up to 250%, compared with control plots (Amede et al. 2011). Farmers have adapted planting basins by increasing their depth and width. For example, the use of 2 m wide *ngoro* pits in Tanzania gave more maize grain yield (1.9 Mg ha^{-1}) compared with 1.5 m wide pits (1.7 Mg ha^{-1}) and 1 m wide pits (1.44 Mg ha^{-1}) (Malley et al. 2004). Planting basins create wet conditions that can have an impact on GHG emissions. Specifically, concentrating nutrients in one spot can create hotspots of GHG emissions. On the other hand, planting basins may improve nutrient use efficiency, as all nutrients are placed close to the plant and within reach of plant roots. No studies relating planting basin to pests and diseases are available in the literature, and therefore, we cannot provide a clear link between planting pits and pests. This shows that practices reviewed respond to certain challenges and not all.

Farmers have found planting basins to be attractive because they reduce the risk of crop loss and provide more options for cropping and bringing into cultivation land previously not suitable for cultivation (Roose et al. 1999; Amede et al. 2011; Zougmoré et al. 2014). However, it is essential to note that digging planting pits is labor-intensive and may represent a shift in labor inputs from men to women in regions where plowing is done by men who use oxen, while women are tasked with digging planting basins (Dahlin and Rusinamhodzi 2019). A shift in labor represents both a risk to women and an opportunity for women's empowerment. Women in programs that use planting basins devise strategies for easing labor through cooperatives. In eastern Kenya, a challenge to planting basins is that farmers prefer maize, even though crops that can occasionally withstand wet and dry soils (e.g., sorghum or pearl millet) are best suited for planting basins. Maize is not suitable, as it is not tolerant of drought or waterlogging (pits are prone to waterlogging during wet years). Another limitation concerns farmer knowledge on the preparation and use of manure. Some farmers apply untreated (fresh) cow dung to planting pits, negatively affecting the emerging crops.

Adoption of planting basins has been low to date, despite widespread diffusion of the practice (Danso-Abbeam et al. 2019). A major bottleneck to greater adoption of planting basins is the high labor requirement. For instance, 450 h are needed for digging *zaï* pits on an area of 1 ha, and 150 h are needed for applying fertilizer in the dug pits (Kaboré and Reij 2004). The high labor requirements make the technology unattractive for resource-constrained farmers incapable of employing additional labor. Large-scale application of planting basins has also been hindered by lack of financial or education support to poor or subsisting farmers. Farm-level policies that aim to increase access to extension services, credit facilities, and the facilitation of farmer groups can improve the adoption of planting basins (Danso-Abbeam et al. 2019).

3.6 Push-pull technology

Push-pull is an innovative cropping system developed for pest management in SSA (Fig. 1d). It has already been adopted by over 237,670 farmers in East Africa (http://www.push-pull.net/adoption.shtml). The practice was initially developed to control stemborers (*Chilo partellus* Swinhoe and *Busseola fusca* Fuller) but has also been shown to control striga weed (Khan et al. 2002). Recently, push-pull was shown to effectively control the invasive fall armyworm (*Spodoptera* *frugiperda* J.E. Smith) (Midega et al. 2018). Push-pull involves intercropping a cereal crop with silverleaf (*Desmodium uncinatum* Jacq.) or greenleaf (*Desmodium intortum* Mill.) desmodium as a push crop and planting Napier grass (*Pennisetum purpureum* Schumach.) or brachiaria (*Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf.) as a border crop (Khan et al. 2014). Desmodium releases two chemicals, one of which repels stemborer moths and attracts their natural enemies, while the other prevents striga from attaching to the maize roots. Napier grass attracts stemborer moths, which lay their eggs on it. When the eggs hatch, the Napier grass releases a sticky substance that limits insect movement, killing the larvae or juvenile stemborers. Desmodium, a perennial plant, is maintained by trimming before planting to minimize competition with the young cereal. It can also be trimmed once or twice during the growing season to provide fodder or mulch. When harvesting the Napier grass, at least one fully grown row is retained to maintain the "pull" service. Other benefits of push-pull include fodder provision, soil erosion control, and soil fertility improvement (Midega et al. 2015).

Push-pull is known to control pests and increase crop yield (Table 1). Several studies show that push-pull is superior in controlling constraints to crop production compared with the traditional cereal-legume intercropping that is a fundamental component of mixed farming systems in Kenya, parts of Uganda, Tanzania and Ethiopia (Khan et al. 2014; Midega et al. 2015). Long-term experiments in these countries show that push-pull can effectively control pests (striga, stem-borer, fall armyworm) and improve soil fertility. In studies comparing push-pull intercrop versus maize or sorghum monocrop (Khan et al. 2006; Midega et al. 2015), desmodium effectively eliminated striga, reducing the weed to negligible amounts. Desmodium suppresses striga through suicidal germination, reducing the seed bank in the soil, shading, and increasing available nitrogen via nitrogen fixation (Khan et al. 2002). The effectiveness of desmodium against striga has been demonstrated in East Africa, where striga is a major constraint to cereal production, and where the intercropping of cereals with legumes such as common beans, soybean, and cowpea has not eliminated the problem of striga in the region (Khan et al. 2006, 2009). Good efficacy of desmodium against striga and stemborer has been demonstrated on including common beans or cowpea in maize-desmodium intercrops (Khan et al. 2006, 2009).

With the integration of drought-tolerant desmodium species, push-pull has evolved into a climate-smart technology that performs well under dry conditions and adapts to common intercropping systems in East Africa. Drought-tolerant desmodium species have been found to effectively suppress parasitic striga weed and improve cereal grain yields in western Kenya (Midega et al. 2015, 2018). Push-pull practices involving *D. intortum* and brachiaria (Mulatto II cultivar) are well adapted to dry areas in western Kenya, eastern Uganda, and northern Tanzania (Midega et al. 2015, 2018). Push-pull has also been integrated into common cereal cropping systems in East Africa.

Even though push-pull has multiple benefits, the high cost of desmodium seeds and insufficient flow of information and training of farmers due to lack of specialist skills have limited farmers' awareness and adoption (Murage et al. 2015). The adoption of push-pull has therefore been slow, despite its great promise. Its uptake has been faster in regions affected by striga. In environments where striga is not a challenge, farmers are often reluctant to replace legumes (e.g., common beans, cowpea, and groundnuts) with fodder species (desmodium) or to reduce maize production area in favor of Napier grass or brachiaria (Kebede et al. 2018). In this case, ownership of livestock and/or the presence of a market for fodder might drive adoption (Ndayisaba et al. 2020). Another example of a driver of adoption is the zero grazing policy in countries like Rwanda, which has created a need to cut and carry fodder to enclosed animals. This policy encourages crop-livestock farmers to find additional niches for fodder production on their farms. Another constraint is the low availability of certified desmodium seeds (Murage et al. 2015). This calls for actions addressing the lack of seeds of both desmodium and Napier grass/brachiaria at farm gates.

3.7 Fertilizer and manure micro-dosing

Traditionally, farmers broadcast manure and fertilizers to supply nutrients to crops. Such approaches are inefficient but common in smallholder systems in SSA. In contrast, micro-dosing administers small amounts of the nutrient source at the right time and close to the seedlings (Tabo et al. 2007; Twomlow et al. 2010). It is widely considered an entry point to sustainable intensification of agricultural systems in dry areas (Twomlow et al. 2010; Adams et al. 2016; Ibrahim et al. 2016a). The practice was first tested in the Sahel (Burkina Faso, Mali, and Niger) and subsequently popularized in Southern Africa (e.g., in Mozambique, South Africa, and Zimbabwe). In practice, a bottle capful or three-finger pinch of fertilizer is placed in a sowing hole or beside a plant (Twomlow et al. 2010). The application of small amounts of fertilizer appeals to farmers because of a good return on investment and low financial risk (Aune et al. 2007; Hayashi et al. 2008). The amount of fertilizer used in micro-dosing is close to one-third of the recommended rate, suggesting efficiency and ability to minimize fertilizer inputs (Hayashi et al. 2008; Ibrahim et al. 2015).

Fertilizer micro-dosing originally targeted maize (Ncube et al. 2007; Twomlow et al. 2010; Tovihoudji et al. 2017), sorghum (Aune et al. 2007), and millet (Ibrahim et al. 2015, 2016a, b; Adams et al. 2016) but has recently been expanded to rice (Vandamme et al. 2018). The technology has increased productivity in areas where high costs previously discouraged poor farmers from using fertilizers (Hayashi et al. 2008; Ibrahim et al. 2015). Cases of increased household income have also been reported (Ibrahim et al. 2015). Increased short-term crop yield across the Sahel has led to upscaling of micro-dosing as an agronomic practice in low-input cropping systems (Adams et al. 2016). A meta-analysis with 165 paired yield outcomes from 33 study sites in 11 countries across SSA reported that micro-dosing improved grain yields by 47% relative to management with no nutrient inputs (Tonitto and Ricker-Gilbert 2016). Experiments on nutrient-depleted farms in Niger, Mali, and Burkina Faso resulted in greater average grain yield of millet and sorghum (44–120%) compared with fertilizer broadcasting methods and other farm practices (Tabo et al. 2007; Bielders and Gérard 2015). More significant yield increases have been observed comparing fertilizer micro-dosing with unfertilized control plots (Aune et al. 2007; Hayashi et al. 2008; Twomlow et al. 2010; Ibrahim et al. 2016b). Micro-dosing has been found to counter the negative impacts of late sowing in semi-arid and arid areas (Bielders and Gérard 2015). The positive effects of fertilizer micro-dosing on yield arise from better exploitation of soil nutrients because of the early production of many lateral roots within the topsoil (Ibrahim et al. 2016b). Micro-dosing also enables plants to grow fast and evade droughts that may occur early in the season. Plants with fast-growing roots can efficiently exploit moisture at greater depths later in the season when soil moisture near the soil surface is low.

While yield benefits, economic returns, and positive farmers' perception on micro-dosing have been reported in many countries (Ncube et al. 2007; Tonitto and Ricker-Gilbert 2016; Vandamme et al. 2018), the technology has limitations and trade-offs that need to be overcome (Hayashi et al. 2008; Twomlow et al. 2010). Manual micro-dosing is labor-intensive and time-consuming, particularly when sowing and micro-dosing are performed in separate operations (Vandamme et al. 2018). Labor demand can be reduced if the technology is mechanized, allowing simultaneous seed sowing and fertilizer application, packaging appropriate fertilizers in small packs, or seed coating with fertilizer (Vandamme et al. 2018). Another limitation of fertilizer micro-dosing is nutrient mining. Evidence from Benin, Mali, and Niger shows that fertilizer micro-dosing enhances crop yields but increases the risk of soil nutrient depletion in low-input cropping systems (Ibrahim et al. 2016a; Tovihoudji et al. 2017). The risk of soil nutrient depletion is generally higher for phosphorus and potassium (Tovihoudji et al. 2017) since these minerals cannot be fixed biologically from the atmosphere by plants. There is also the risk of soil nutrient imbalances if crop nutrient uptake exceeds the amount added through micro-dosing (Nziguheba et al. 2016). Consequently, crop yield is higher at the beginning of fertilizer micro-dosing but eventually declines as crop response to fertilizer wanes over time (Adams et al. 2016; Tovihoudji et al. 2017). Nutrient mining and nutrient imbalances can be averted by combining micro-dosing with organic amendments, e.g., use of organic manure or compost (Ibrahim et al. 2016a; Tonitto and Ricker-Gilbert 2016), or complementing it with sustainable practices such as intercropping with nitrogen-fixing legumes or retaining crop residues (Ibrahim et al. 2016a).

Studies conducted in West and Southern Africa suggest that micro-dosing adoption requires conducive and supportive institutional arrangements and input and output market linkages (Mwinuka et al. 2017). Current institutional arrangements limit access to fertilizer, credits, training, and information flow to farmers, creating bottlenecks to adopting micro-dosing. Compared with recommended levels, micro-dosing produces lower yields and is less profitable (Ibrahim et al. 2016a). Reduced profitability, coupled with other institutional constraints, limits the adoption of the technology. Micro-dosing is currently limited to cereal monocrops and has not been tested for intercropping or mixed cropping systems characteristic of smallholder farmers in SSA.

4 Potential for reducing the carbon footprint of agriculture

Africa's contribution to global carbon emissions is mainly driven by a rapidly increasing population causing cropland expansion, land degradation, and increased deforestation risks (Ciais et al. 2011). The net release of carbon from land-use change and forestry in SSA is estimated to be 0.24 Pg C $year^{-1}$ (Ciais et al. 2011). Agriculture is the second-largest contributor to GHG emissions in terms of CO_2 eq. (Fig. 5), contributing about 31% of Africa's total emissions. Agricultural GHG emissions in the region are projected to increase, while the energy sector's GHG contributions are expected to decrease by 2050 (Fig. 5b).

The agronomic practices reviewed here show large yet varying potential for offsetting GHG emissions from agriculture. Most practices can lower emission intensities by increasing the amount of carbon stored in the soil (e.g., intercropping, CA, agroforestry) and biomass (e.g., agroforestry). For example, intercropping and CA have been suggested as practices that potentially increase soil organic carbon in dryland conditions (Hobbs et al. 2008). On sandy soils of SSA, technologies that increase soil water retention (thus increasing crop productivity) may significantly increase soil carbon sequestration (Nkurunziza et al. 2019). Furthermore, tree species used in various agroforestry practices sequester significant amounts of carbon in biomass and soil. Table 2 shows the estimated carbon uptake in a 20-year rotation cycle.

The agronomic practices reviewed can lower emission intensities by reducing direct and indirect soil N_2O emissions. In croplands, high N_2O emissions result from adding extra nitrogen inputs in the form of organic nitrogen (e.g., practices

Table 2 Mean annual increment (MAI, C ha^{-1} $year^{-1}$) rate and carbon dioxide equivalents (t C ha^{-1} CO_2 eq.) in tree biomass estimated assuming a 20-year rotation in various agroforestry practices and forests/woodlands in Southern Africa

Agroforestry practice	Species	Country	Age (years)	MAI	CO_2 eq. (t ha^{-1})	Reference[¥]
Improved fallow	*Tephrosia vogelii*	Zambia	3	2.8	NA	1
	Sesbania sesban	Zambia	3	2.7	NA	1
	Cajanus cajan	Zambia	3	2.5	NA	1
Intercropping	*Leucaena leucocephala*	Zambia	10	3.2	234.9	1
	Gliricidia sepium	Zambia	10	2.9	212.9	1
	Calliandra calothyrsus	Zambia	10	2.7	198.2	1
	Senna siamea	Zambia	10	2.6	190.8	1
Parkland	*Faidherbia albida*	Tanzania	6	1.2	88.1	2
Woodlots	*Acacia auriculiformis*	Tanzania	5	2.3	168.8	3
	Acacia crassicarpa	Tanzania	5	5.1	374.3	3
	Acacia julifera	Tanzania	5	3.1	227.5	3
	Acacia leptocarpa	Tanzania	5	3.8	278.9	3
	Acacia mangium	Tanzania	5	3.8	278.9	3
	Acacia nilotica	Tanzania	5	2.3	168.8	3
	Acacia polyacantha	Tanzania	5	3.6	264.2	3
	Gliricidia sepium	Tanzania	5	2.9	212.9	3
	Leucaena diversifolia	Tanzania	5	3.4	249.6	3
	Leucaena pulverulenta	Zambia	7	8.0	587.2	4
	Leucaena collinsii	Zambia	7	4.3	315.6	4
	Leucaena diversifolia	Zambia	7	4.7	345.0	4
	Leucaena leucocephala	Zambia	7	4.6	337.6	4
	Leucaena macrophylla	Zambia	7	3.5	256.9	4

[¥] References represent the sources of carbon accumulation rates: 1 = Kaonga and Coleman (2008); 2 = Okorio and Maghembe (1994); 3 = Kimaro et al. (2011); 4 = Kaonga and Bayliss-Smith (2009); NA = not applicable because rotations for improved fallow only take 2–3 years

including nitrogen-fixing plants with nitrogen-rich plant residues) or inorganic nitrogen (Valentini et al. 2013). Generally, crops that receive a lot of fertilizer (e.g., cereal monocultures) have a high carbon footprint, while those that fix nitrogen and are not fertilized or receive less fertilizer (e.g., legumes) typically have a small carbon footprint. For example, conventionally produced maize in South Africa is estimated to have a carbon footprint as low as 0.6 t CO_2 eq. ha^{-1} (Tongwane et al. 2016). In Zambia, average annual emissions from maize production at three different intensities of nitrogen fertilizer use (0, 25, 85 kg N ha^{-1}) were estimated to range between 0.1 and 0.6 t CO_2 eq. ha^{-1} (FAO 2015). On the other hand, leaf biomass from agroforestry when applied at 5 Mg ha^{-1} can provide N inputs of 60–150 kg ha^{-1}, and this can support maize yields of up to 4 Mg ha^{-1} without any added synthetic fertilizer (Sileshi et al. 2014). In Gliricidia-maize intercropping in Malawi, Kim (2012) demonstrated the possibility to reduce synthetic fertilizer use by 48 kg N ha^{-1} $year^{-1}$ while still maintaining yields of up to 4 Mg ha^{-1} and avoiding GHG emissions amounting to 0.48 kg N_2O ha^{-1} $year^{-1}$ (Kim 2012). The system was also estimated to mitigate 3.5–4.1 t CO_2 eq. ha^{-1} $year^{-1}$ (Kim 2012).

Soil N_2O emissions from African agroforestry (4.7 kg N_2O ha^{-1} $year^{-1}$) are comparable with those from croplands (4.0 kg N_2O CO_2 ha^{-1} $year^{-1}$) (Kim et al. 2016). However, soils under agroforestry are reported to be net CH_4 sinks. For instance, according to a recent synthesis (Kim et al. 2016), soils under agroforestry oxidize 1.6 kg CH_4 ha^{-1} $year^{-1}$. The most considerable reduction in net CH_4 emissions has been recorded under improved fallow, with net soil CH_4 emissions being reduced with a shift from cropping to agroforestry systems (Kim et al. 2016).

Legumes used in push-pull technology, cereal-legume intercropping, and doubled-up legume technology reduce reliance on nitrogen fertilizer inputs and lower the GHG cost of fertilizer production. Push-pull practices can also reduce emissions related to the production of herbicides and pesticides that would otherwise be needed to control stem-borer, fall armyworm, and striga. However, as shown by a study conducted in Denmark, leguminous plants can be a source of N_2O from legume-derived nitrogen, especially during residue decomposition (Pugesgaard et al. 2017).

Micro-dosing customizes the addition of nutrients to plant uptake, thereby reducing emissions of N_2O. Direct and indirect soil N_2O emissions and CO_2 from fertilizer and machinery manufacturing (in the case of mechanized micro-dosing) and CO_2 from field operations can be expected to be lower than those associated with fertilizer banding or broadcasting. Planting basins and push-pull technology reduce GHG emissions as they result in a decrease in the overall area under tillage and thus reduce the amounts of fuel-based GHG emissions on farms. Significant data gaps exist regarding the contribution of specific innovations such as push-pull to carbon sequestration and GHG emission reductions related to crop protection products.

5 Conclusions and recommendations

The agronomic practices identified here are important because they can simultaneously increase crop productivity and, in certain situations, support provisioning of other ecosystem services, while also reducing the carbon footprint of agriculture. Uptake of these agronomic practices can transform existing crop management and contribute to sustainable intensification in regions where they are not yet adopted. Agroforestry, legume-cereal intercropping, and push-pull are diverse systems and harness ecosystem services from perennials to increase productivity. These innovations can also diversify and increase household incomes from increased crop yields and improved resource use. For example, CA and planting basins conserve water, while planting basins and micro-dosing can improve nutrient targeting and reduce input costs.

Regardless of the capacity of technological or management innovations to increase crop yields and incomes, they will have limited impacts if not adopted at scale. To achieve large-scale adoption, there is a need to overcome barriers to adoption, namely, limited financing, lack of a supportive policy and regulatory environment, lack of specialist extension services, shortage of labor, lack or high cost of inputs such as seeds or planting material, and low degree of mechanization (Kamanga et al. 2014; Murage et al. 2015; Dahlin and Rusinamhodzi 2019; Danso-Abbeam et al. 2019). Policy and regulatory authorities need to formulate creative policies and regulations that incentivize the adoption of promising options. For example, policies that ensure reduction in taxes and, consequently, retail prices for critical fertilizers may improve affordability and access to fertilizer inputs and incentivize their use by smallholder farmers. Lack of financial resources to cover input costs can be tackled through creative financing (Lipper et al. 2014). For instance, good availability of low-cost credit facilities for farmers, linked to technology adoption and guaranteed expert support services, can promote adoption and ensure access to crucial knowledge.

One major challenge in smallholder agriculture is its over-reliance on family labor. Rural-urban migration and a general lack of interest in agriculture among the young generation result in labor shortages that may limit adoption of labor-demanding innovations such as doubled-up legume, push-pull, fertilizer, and manure micro-dosing. To overcome the labor challenges, there is a need to develop and promote labor-saving equipment and mechanization as an essential aspect of sustainable intensification of smallholder agriculture in SSA. Considering the challenges in access to information and training of farmers (for technologies that require specialist skills), there may be an opportunity to recruit unemployed local young people to rapid training courses covering the essentials of extension work and then employing them as para-extension workers. These para-extension workers could initially be restricted to the main agricultural products grown in specific locations and improvements based on new research findings. Accessibility of farmer support services could help farmers embrace GAP, especially in communities that consume what they produce locally.

Finally, the management and technological approaches identified here can contribute to food security and improve livelihoods in the SSA region. However, synergies must be explored to maximize benefits derived from combining the various innovations. For example, fertilizer micro-dosing can be combined with basin planting (e.g., *zaï* pits). Planting basins can also be beneficially combined with contour or stone bunds and agroforestry practices (Bayala et al. 2012). Specific CA practices, such as crop rotation, intercropping with legume cover crops, and no-till ridging, can be adapted in different farming systems by smallholders who do not have the resources to buy herbicide or mechanize farm power. We recommend policy advocacy, input financing, capacity development, and strengthening extension advisory services to achieve large-scale adoption of these practices.

Authors' contributions Shem Kuyah and Gudeta W. Sileshi designed the structure and formulated the aims of the manuscript. Libère Nkurunziza, Ngonidzashe Chirinda, Pierre Celestin Ndayisaba, Kangbéni Dimobe, and Ingrid Öborn contributed to the data analysis, literature review, and writing and editing of different sections of the manuscript.

Funding Open access funding provided by Swedish University of Agricultural Sciences.

Data availability Not applicable.

Code availability Not applicable.

Declarations

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

Consent for publication Not applicable.

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