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RESEARCH ARTICLE

Tropical forage technologies can deliver multiple benefits in Sub-Saharan Africa. A meta-analysis

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Abstract

Scarcity of quantity and quality feed has been a key constraint to productivity of smallholder crop-livestock systems. Tropical forages include a variety of annual and perennial grasses, herbaceous and dual-purpose legumes, and multipurpose trees and shrubs. They have been promoted in Sub-Saharan Africa (SSA) for increasing livestock productivity and household income through higher quantity and quality of herbage, while contributing to soil improvement and higher food crop yields. For the first time, we quantitatively reviewed 72 experimental studies from across SSA to take stock of geographical distribution and forage technology focus of past research; quantify magnitudes of multidimensional impacts of forage technologies; and present variability in forage agronomy data. Improved forage technologies were classified into four groups: (i) germplasm, (ii) management, (iii) cropping system integration, and (iv) feeding regime. Mean weighted response ratios were calculated from 780 pairs of observations for 13 indicators across the five impact dimensions. Improved forage germplasm had on average 2.6 times higher herbage productivity than local controls, with strongest effect in grasses. Feeding regimes with improved leguminous forages increased milk yield by on average 39%, dry matter intake by 25%, and manure production by 24%. When forage technologies were integrated with food crops, soil loss was almost halved, soil organic carbon increased on average by 10%, and grain and stover yields by 60% and 33%, respectively. This study demonstrates the central role improved forages could play in sustainable intensification of crop-livestock systems in SSA. It highlights the need for multidisciplinary and systems-level approaches and studies to quantify synergies and tradeoffs between impact dimensions. Further research is needed to explain forage agronomic yield variability, unraveling interactions between genotype, on-farm environmental conditions, and management factors. Results from this review can inform development programs, prioritizing technologies proven successful for dissemination and indicating magnitudes of expected impacts.

Keywords Crop-livestock systems · Herbaceous legume · Forage grass · Soil organic carbon · Livestock productivity · Forage agronomy · Cropping system · Multi-dimensional impacts · Sustainable intensification

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1 Introduction

Two-thirds of the global rural population are engaged in mixed crop-livestock systems, and these farmers produce around 50% of the world's cereals, 60% of meat, and 75% of milk. Mixed systems enable farmers to synergize between cropping activities and livestock husbandry through draft power for land cultivation, manure application for crop fertilization, and feeding of crop residues and planted forages (Herrero et al. 2010). Scarcity of quantity and quality livestock feed on a consistent basis is often cited as a major constraint faced by mixed crop-livestock farmers in Sub-Saharan Africa (SSA), especially during the dry season. Feed is also a major production cost in dairy production (Bebe et al. 2008; Hall et al. 2007). SSA has one of the lowest feed conversions for milk and meat globally, thus, the highest amounts of feed needed to produce a unit livestock product. This is mainly due to low animal productivity and poor livestock diets in smallholder mixed systems, as they rely on crop residues, grazing, collected vegetation, and other opportunistic feed (Herrero et al. 2013). Crop residues are often of low feed quality, and scarce resources on smallholder farms due to their competing uses as soil amendment (Homann Kee-Tui et al. 2014; Tittonell et al. 2015; Valbuena et al. 2012; Tittonell et al. 2015).

One of the main approaches for addressing the feed scarcity has been to develop improved feed and forage options, and evaluate them for their yield and quality, and impact on livestock productivity parameters (Ayele et al. 2012; Hall et al. 2007). Improved tropical forages include a wide variety of sown or planted grasses, herbaceous or dual-purpose legumes, and multipurpose trees and shrubs (also mostly legumes) that are integrated in agropastoral, silvopastoral, and intensive or extensive mixed agricultural systems for grazing or cut-and-carry (Rao et al. 2015). Intensification with improved forage technologies can take two forms: simple improvements such as the introduction of new forage varieties on-farm and in the existing feeding regime, or more complex sets of new practices that integrate forages in production systems. Forages need to be integrated into cropping systems, especially with food crops, to not compromise smallholders' food security (Ates et al. 2018; Maass et al. 2015; Rudel et al. 2015). Tropical forages can fulfill various objectives and roles in farming systems, and they can occupy different spatial and temporal niches. In a crop role, herbaceous and dual-purpose legumes can be sown on arable land to meet short-term or seasonal fodder needs; in a niche role, herbaceous and dual-purpose legumes and trees/shrubs can be grown on farm boundaries, fallows, roadsides, and crop under-story, to meet planned and opportunistic fodder needs; or in a companion role, they can be sown as grass-legume pasture to satisfy long-term feed requirements (Lenné and Wood 2004; Peters et al. 2001).

Tropical forage biomass is usually an intermediate product primarily aiming at increasing livestock productivity. In addition to increasing milk and meat production, they can also contribute to other production objectives such as reducing risks in the face of feed scarcity, increasing yields of associated food crops through weed suppression, pest and disease reduction (in rotations or as intercrop), and increased manure quantity and quality for crop fertilization (Peters et al. 2001; White et al. 2013). Tropical forage technologies are also reported to have environmental cobenefits, including soil rehabilitation and soil quality improvement. Forage grasses can increase carbon accumulation through their deep-rootedness and perennial nature. Forage legumes can improve soil fertility through nitrogen fixation, and increase water efficiency through deep reaching taproots. Pioneering species such as *Stylosanthes* spp. have the potential to rehabilitate severely degraded land. Grasses, legumes, and trees/shrubs, when planted as hedgerows, cover crops, or live barriers, can reduce soil erosion and runoff (Rao et al. 2015; Schultze-Kraft et al. 2018). Climate change mitigation can be achieved through increased carbon accumulation particularly in deeper soil layers, reduced methane emission intensity from enteric fermentation through higher nutritional value and digestibility of feed, lower nitrous oxide emissions from soils through biological nitrification inhibition (BNI) capacities of selected grasses, and increase of aboveground carbon through integration of fodder trees in silvopastoral systems (Peters et al. 2013). The potential, multidimensional benefits of improved forages in smallholder systems in SSA are summarized in Fig. 1.

Research on tropical forages in SSA has been spread over time and regions. Yet a comprehensive, quantitative overview of forage technologies, as well as ranges and magnitudes of their multidimensional impacts, is currently lacking. This study aims to take stock of the state of forage research in SSA by conducting a systematic, quantitative literature review with the following objectives: (i) provide an overview of geographical distribution and forage technology focus of past research; (ii) quantify magnitudes of impacts of tropical forage technologies on forage productivity and quality, livestock productivity, soil quality, economic performance and food crop productivity at plot, animal and household level; and (iii) present the variability of forage agronomy data.

2 Materials and methods

2.1 Literature search and study selection

We performed a systematic literature search in June 2016 to compile peer-reviewed articles. We used the scientific search engine Scopus, employing the following search terms: "livestock", "feeds" OR "forage" OR "fodder", and "Africa". We

Fig. 1 Improved tropical forage technologies have been promoted for use in smallholder systems in Sub-Saharan Africa (SSA) for their potential multiple benefits: increased herbage productivity and better nutritive quality, leading to increased livestock productivity (meat, milk, manure), soil quality (erosion, carbon, nutrients), economic performance of the household, and food crop productivity (grains and stover). Photo credits: B.K. Paul (forages, livestock + manure, soil), G. Smith, CIAT (economics) and B.L. Maass (food crop)

complemented this search with references cited in the primary literature and unpublished studies obtained from the authors' personal networks. For inclusion into this review, we only selected studies that met the following criteria: (1) The study reported empirically measured, original data on one of the target impact indicators (see section 2.2), excluding simulated data or data cited in reviews or secondary articles; (2) the article examined at least one tropical forage technology (grass, herbaceous or dual-purpose legume, leguminous multipurpose trees, and shrubs hereafter called "shrubs") but not cereal crop residues, concentrates or tree products—if the technology was a dual-purpose legume, it was only included if the forage or livestock impact was assessed as well; (3) the article focused on ruminant livestock, excluding monogastrics; (4) the study reported data from experimental, "improved" treatments and a control treatment; (5) the reported data was continuous and numerical thus not reported in scores, ranks, percentages or as graphs; (6) the study was written in English; (7) basic experimental information was available in section 2; and (8) the study was conducted in Sub-Sahara Africa. Using these criteria, 72 studies were found suitable to be included in the review (see references of review). These studies were published over 30 years between 1985 and 2015 (Fig. 2a). For each of the 107 experimental sites across the 72 studies, we extracted the reported geographical location. If precise geographical coordinates were not reported in the publication, we chose the center of the lowest-level known administrative unit and added GPS coordinates extracted from Google maps. We mapped the dominant livestock production system of all study locations (Robinson et al. 2011) (Fig. 2b).

2.2 Forage technologies, impact dimensions, and data retrieval

Forage technologies were classified as follows: (a) Germplasm referring to newly introduced forages (i. grass; ii. herbaceous legume; iii. dual-purpose legume) that were tested in on-station or on-farm trials against a local control forage; (b) Management comprising (i) fertilization regimes (mineral fertilizer and manure) and (ii) planting method such as manure application in planting holes, and compared treatment performance to the farmers' practices; (c) Cropping system integration describing (i) forage grass and/or shrub planted as hedgerow with food crops, (ii) forage grass, legume, and/or shrub intercropped with food crop, or (iii) forage grass intercropped with forage legume; (d) Feeding regime including the supplementation of basal feed like residues or grasses with leguminous forages, fed as either fresh biomass, or vines, haulms, hay or leaf meal—forages can be (i) herbaceous legume, (ii) dual-purpose legume, or (iii) shrub (Table 1). Throughout this study, we are using the scientific names of forages under which the studies were published

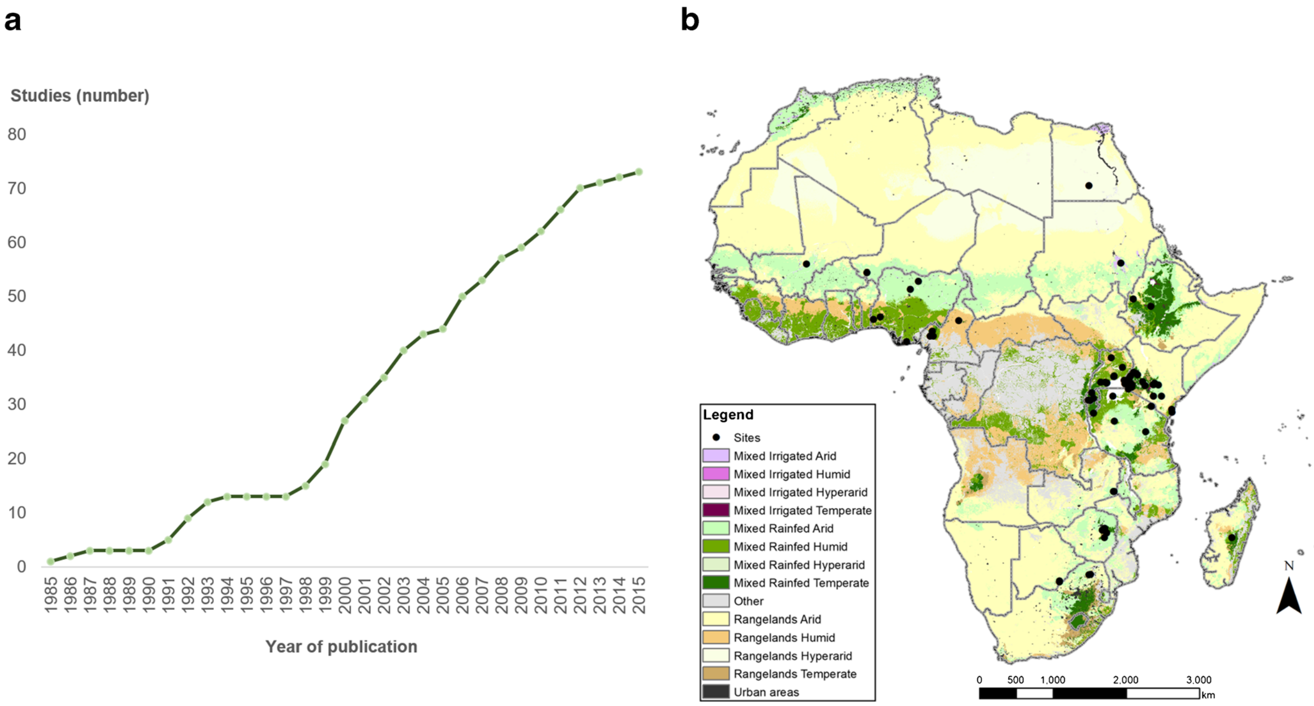

Fig. 2 Cumulative number of studies included in this review per publication year (**a**), and the 107 experimental study sites from all studies mapped on dominant livestock production systems across SSA (Robinson et al. 2011) (**b**). The studies were obtained through a systematic search of peer-reviewed literature in 2016, which was complemented with references cited in primary literature and unpublished studies obtained for the authors' personal networks. Using seven selection criteria, 72 studies were found suitable to be included in the review, published since 1985. If geographical coordinates were not reported in the publication, we chose the center of the lowest-level known administrative unit and added GPS coordinates extracted from Google maps. Studies were conducted across 15 countries in SSA, most of which in East Africa (49). Most sites were located in the mixed rainfed crop-livestock zones (24 sites humid, 23 sites tropical highlands/temperate), and only five sites in rangeland areas (four arid, one hyperarid)

despite the fact that many important species have recently changed, e.g., all *Brachiaria* spp. to *Urochloa* spp., Napier grass (*Pennisetum purpureum*) to *Cenchrus purpureus*, and *Panicum maximum* to *Megathyrsus maximus*, among many more (Cook and Schultze-Kraft 2015).

Effects of forage technologies on five impact dimensions were considered, which loosely follow the economic, social, and environmental domains outlined in White et al. (2013) and Rao et al. (2015): (i) forage productivity and quality—herbage dry matter (DM) yield, crude protein (CP), and metabolizable energy (ME) contents; (ii) livestock productivity—milk yield, dry matter intake (DMI), manure production, and nitrogen (N) content in manure; (iii) soil quality—soil loss (SL), soil organic carbon (SOC); (iv) household economics—revenue and benefit; and (v) food crop productivity—grain and stover yields. Data was extracted from the 72 selected papers into a Microsoft Access database. In addition to impacts, we extracted experimental and technology descriptions including type of technology and forage species, cropping system, management, and number of replications (N). Figure 3 summarizes the number of studies and pairs of observations (treatment—control) per impact dimension and indicator (columns) and technology groups (rows) that are reported in this review. Improved germplasm effects on forage productivity and quality, cropping system integration effects on soil quality, household economics, and food crop productivity were shown as overall average impacts as well as by technology subgroup (plain color). The technologies falling under improved management and cropping system integration were considered to be too diverse to be presented as average impact values across all technologies. Effects of improved management and cropping system integration on forage productivity were only shown as average impacts by technology subgroup (striped pattern). Results were calculated from a total of 780 pairs of observations (Fig. 3).

2.3 Data analysis

We used methods such as weighted response ratios from the field of metaanalysis (Hedges et al. 1999) to quantify magnitudes of effects of tropical forage technologies on forage productivity and quality, livestock productivity, soil quality, economic performance, and food crop productivity. Similar to Delaquis et al. (2018), the breadth of technologies and effects included in the study, and the lack of quality of reported agronomic data (e.g., failure to report variance), resulted in a lack of directly comparable measures, indicators, and variables. Therefore, this study could not take a complete

Table 1 Forage technology groups and forage species included in the review. The scientific names of forages under which the studies were published are used despite recent name changes (i.e., *Brachiaria* spp. to *Urochloa* spp., *Pennisetum purpureum* to *Cenchrus purpureus*, and *Panicum maximum* to *Megathyrsus maximus* in the grasses; *Centrosema pubescens* to *C. molle* and *Pueraria phaseoloides* to *Neustanthus phaseoloides* in the legumes) following Cook and Schultze-Kraft (2015)

Technology	Technology subgroup	Forage species
a) Germplasm: Newly introduced forage germplasm—compared with local species as control	i Grass	*Brachiaria brizantha/B.* hybrids/*B. decumbens*, *Pennisetum purpureum*
	ii Herbaceous legume	*Stylosanthes guianensis, Centrosema macrocarpum/C. pubescens*, *Pueria phaseoloides*, *Mucuna pruriens*, *Desmodium heterocarpon-ovalifolium*, *Zornia glabra*, *Dioclea guianensis*, *Arachis pintoi*, *Aeschynomene histrix*, *Flemingia macrophylla*
	iii Dual-purpose legume	*Vigna unguiculata*
b) Management: Improved agronomic measures applied to forage dual purpose and herbaceous legumes and grasses - compared to same crop without improved agronomy as control	i Fertilizer	*Pennisetum purpureum*, *Lablab purpureus*, *Desmodium uncinatum*, *Mucuna pruriens*, *Stylosanthes scabra*, *Macroptilium atropurpureum*
	ii Planting method	*Pennisetum purpureum*
c) Cropping system integration: Forage dual purpose and herbaceous legumes, grasses and shrubs are combined with food crops as hedgerow or intercrop, and forage legume and grass intercropped - compared to same situation without combination as control	i Grass/shrub hedgerow with food crop	*Pennisetum purpureum*, *Calliandra calothyrsus*, *Leucaena leucocephala/L. diversifolia*, *Sesbania sesban*
	ii Grass/legume/shrub intercrop with food crop	*Desmodium uncinatum/D. intortum*, *Pennisetum purpureum*, *Chloris gayana*, *Vigna unguiculata*, *Lablab purpureus*, *Stylosanthes fruticosa/S. hamata*, *Mucuna pruriens*, *Clitoria ternata*, *Cajanus cajan*, *Vigna trilobata*, *Gliricidia sepium*, *Sesbania sesban*
	iii Grass-legume association	*Desmodium uncinatum/D. intortum*, *Pennisetum purpureum*, *Brachiaria spp*, *Arachis pintoi*, *Stylosanthes scabra/S. guianensis*, *Macroptilium atropurpureum*, *Panicum maximum*, *Clitoria ternatea*, *Tripsacum laxum*, *Setaria splendida*, *Macrotyloma axillare*, *Centrosema molle*
d) Feeding regime: Supplementation of basal diet with improved, mostly leguminous forages as fresh biomass, vines, haulms, hay or leaf meal - compared to basal diet as control	i Herbaceous legume	*Desmodium intortum*, *Canavalia ensiformis*, *Centrosema macrocarpum*, *Macroptilium atropurpureum*, *Neontonia wightii*, *Stylosanthes scabra/S. guianensis*, *Mucuna pruriens*, *Medicago sativa*, *Aeschynomene histrix*
	ii Dual-purpose legume	*Arachis pintoi*, *Cajanus cajan*, *Lablab purpureus*, *Vigna unguiculata*
	iii Shrub	*Calliandra calothyrsus*, *Leucaena leucocephala*, *Gliricidia sepium*, *Sesbania sesban*, *Colospermum mopane*

metaanalysis approach fulfilling all the criteria laid out by Philibert et al. (2012), including analyzing the heterogeneity of data with random-effect models, sensitivity analysis, and investigation of publication bias.

We quantified the effect of forage technologies on the impact indicators (see section 2.2) calculating response ratios (RR) for individual observations:

$$RR = \left(\frac{X_E}{X_C}\right)$$

where X_E is the impact indicator value for the forage technology treatment, and X_C is the impact indicator value for the control treatment.

For most observations in our dataset, the original studies did not report measures of variance. Consequently, we relied on a nonparametric approach to weighing observations instead of using the inverse of the pooled variance. Effect sizes were weighed by replication to assign more weight to well-replicated studies:

$$W_R = \frac{N_C * N_E}{(N_C + N_E)}$$

where W_R is the weighing factor by replication, N_C the number of treatments per control, and N_E the number of replicates per experimental treatment. If no N was reported for a study, $N = 1$ was assumed.

Multiple observations from the same field site or several treatments with only one control are not independent, and this

		Forage productivity and quality			Livestock productivity				Soil quality		Household economics		Food crop productivity	
Technology	**Sub-group**	DM	CP	ME	Milk	DMI	Man	Man N	SL	SOC	Rev	Ben	Grain	Stov
Germplasm	i. Grass	2/25	1/18											
	ii. Herbaceous legume	1/2												
	iii. Dual-purpose legume	1/6												
Management	i. Fertilizer	1/14												
	ii. Planting method	6/74	1/7											
Cropping system integration	i. Grass/shrub hedgerow with food crop								4/74	1/5		1/4	4/80	
	ii. Grass/legume/shrub intercrop with food crop									1/9	6/43	4/38	13/182	3/40
	iii. Grass-legume association	11/68	7/17	2/2										
Feeding regime	i. Herbaceous legume				5/14	6/15		1/2						
	ii. Dual-purpose legume				5/6	4/6	2/3	2/3						
	iii. Shrub				5/14	5/9								

Fig. 3 Number of studies and pairs of observations (treatment–control) of this review reported in brackets. Impact dimensions and indicators are listed in columns, and technology groups in rows. Results were calculated from a total of 780 pairs of observations. Colors differentiate impact dimensions: forage productivity and quality (green shades), improved feeding regime on livestock productivity (grey shades), improved cropping system integration on soil quality (red shades), household economics (blue shades), and food crop productivity (brown shades). Germplasm effects on forage productivity and quality, cropping system integration effects on soil quality, household economics, and food crop productivity were shown as overall average impacts (see Fig. 4) as well as by technology subgroup (see Fig. 5) (plain color). Effects of improved management and cropping system integration on forage productivity were only shown as average impacts by technology subgroup (see Fig. 5) (striped pattern)

needs to be accounted for in the weights. To avoid bias, the weighing factor by replication was, thus, further divided by the number of measurements and treatments:

$$W_o = \frac{W_R/_T}{M}$$

where W_o is the overall weighing factor per observation, W_R is the weighing factor by replication, T the number of treatments per respective control, and M the number of measurements per treatment. This ensured that all experimental comparisons in multifactor and multiyear studies could be included in the data set without dominating the overall effect size.

Mean effect sizes for the overall sample and per technology type were estimated as follows:

$$\overline{RR} = \frac{\sum(RR_i{*}W_{Oi})}{\sum W_{Oi}}$$

With RR_i being the effect size of the ith comparison, and W_{Oi} the overall weighing factor for the ith comparison.

Standard errors were calculated. Indicator units differed between studies, but standardization was not considered necessary for computation of response ratios.

3 Results and discussion

3.1 Geographical distribution of research and characterization of forage technologies

Analyzing the retrieved studies in terms of their geographical locations, technologies, and impact dimensions aimed to reveal and explain focus of past research. The 72 experimental studies included in the review were published between 1985 and 2015, with a peak in the period from 1999 to 2007 (Fig. 2a). Studies were conducted in 15 countries. Within East Africa (49 studies), most studies reported results from Kenya (29). Nine studies were conducted in West Africa, nine in Southern Africa, and five in Central Africa. Most sites were located in the rainfed mixed crop-livestock zones (24 sites humid/subhumid, 23 sites tropical highlands/temperate), and only five sites in rangeland areas (four arid/semiarid, one hyperarid) (Fig. 2b). Studies included a wide variety of forage grasses, legumes, and shrubs (Table 1).

Distinct differences in forage technology research focus per region become apparent. Planted grasses (mainly *Pennisetum purpureum* and *Brachiaria* spp.) and multipurpose shrubs (*Calliandra* spp., *Leucaena* spp., and to a lesser extent *Sesbania*) dominate past research in East Africa, including their intercropping with food crops (maize, and to a lesser extent sorghum and millet) and hedgerow cropping of fodder shrubs and grasses with maize and soybean, and wheat and beans. In West Africa, herbaceous legumes (mainly *Stylosanthes* spp., *Desmodium* spp., *Mucuna pruriens*) and dual-purpose legumes (mainly *Lablab purpureus* and *Vigna unguiculata*) research has been most prominent. Perennial intercropped herbaceous legumes were undersown or relay-planted, and often allowed to grow throughout the following season(s) as improved fallow. Only a few experimental studies from Southern Africa were identified. Four of the nine total studies were conducted in Botswana, and focused either on leguminous shrubs or forage legumes, with only one study on forage grass-legume association (*Brachiaria* hybrid cv. Mulato and *Arachis pintoi*) (Table 1; References of the metaanalysis).

The regional differences in amount of studies and specific species reflect the different production systems, agro-ecologies as well as presence of research centers. The International Livestock Research Institute (ILRI), the International Center for Tropical Agriculture (CIAT), and the International Center for Agricultural Research in the Dry Areas (ICARDA) and regional networks have been leading the international forage research in SSA over the last 30 years, with a focus on breeding and germplasm evaluation. In the national agricultural research systems (NARS), programs were established in the 1960s and 1970s to test and adapt novel forage species and superior genotypes. In the 1990s, a strong movement started towards participatory research to match varietal characteristics with needs and interests of smallholder livestock keepers (Boonman 1993; Hall et al. 2007; Stür et al. 2013). The focus on temperate, humid, and subhumid areas might be explained with higher perceived chances of success of planted forages in mixed crop-livestock systems. Pastoral communities, often concentrating in arid and semi-arid regions, are unlikely to invest in new forages for communally grazed pastures until joint grazing management strategies are in place (Nyariki and Ngugi 2002). There tends to be cultural reluctance to grow forages if producers are unfamiliar with the concept of investing labor for planting, management, and harvesting, as well as capital for seeds and land for feed that was previously "for free". Such investment is mostly common for food crops but not for feed (Thomas and Sumberg 1995).

The advancement of Kenya's dairy industry has been largely based on the wide-spread use of *Pennisetum purpureum* (Pengelly et al. 2003) which has been extensively researched by ILRI and national partners. Its high biomass production with equally high water and soil fertility requirements made it suitable to sub-humid, high-potential highland systems where land availability is limited due to high population pressure. The World Agroforestry Center (ICRAF) and partners promoted agroforestry with multipurpose shrubs and trees with a focus on cut-and-carry systems in eastern Africa. *Calliandra calothyrsus* is most commonly planted as it is fast growing and tolerant to frequent cuttings. However, it is not as nutritious as other species including *Leucaena leucocephala* and *L. trichandra*, and *Sesbania sesban*. Key advantages include that they require little land, and contributions to firewood and erosion control (Place et al. 2009; Franzel et al. 2014).

In West Africa, *Stylosanthes guianensis* and *S. hamata* (Stylo), *Mucuna pruriens* (Mucuna), *Centrosema pascuorum*, and *Aeschynomene histrix* have been promoted for use in fodder banks and improved fallows by ILRI and its national partners. These technologies aimed to alleviate feed stress of agropastoralists in subhumid zones, especially during the long dry season. For a large part of the dry season, a fodder bank planted with herbaceous legumes close to the homestead can maintain a crude protein content of 9% compared with < 7% of the naturally available pastures during that time. Those legumes can also increase subsequent crop yields on the same plot due to nitrogen fixation and improvement of physical soil quality. Stylo has been introduced and promoted since the late 1970s, and Mucuna since the late 1980s (Elbesha et al. 1999; Tarawali et al. 1999). Dual-purpose cowpea (*Vigna unguiculata*) is another crop that has been developed and promoted for mixed crop-livestock systems in the dry savannah zones of West Africa by ILRI and the International Institute for Tropical Agriculture (IITA). Various dual-purpose cowpea varieties have been developed and tested that can deliver benefits on household food productivity, livestock feed, soil quality, and nutrient cycling. Improved dual–purpose cowpea varieties could replace traditional varieties that have been used to either produce grain or fodder (Kristjanson et al. 2002, 2005; Lenné et al. 2003; Tarawali et al. 2003). However, it is important to note that focus on literature published in English has led to a bias against francophone literature from West and Central Africa.

3.2 Magnitudes of multidimensional effects of forage technologies

Calculating average technology effects on selected indicators aimed to quantify the multidimensional impacts of tropical forages on forage productivity and quality, livestock productivity, soil quality, economic performance, and food crop productivity at plot, animal, and household level.

Most studies reported data on only one impact dimension, while it was studies on improved cropping system integration that assessed several dimensions such as forage productivity, soil quality, and food crop productivity (Fig. 3). In a global review of forage impact studies, White et al. (2013) also found that only few studies included various impact dimensions and tradeoffs.

A total of 233 observations reported impacts of forage technologies on forage productivity and quality (Fig. 3). Average herbage productivity of improved forage germplasm technologies was 2.65 times higher than the local controls, and CP content 18% higher (Fig. 4). When differentiating forage productivity impacts by technology groups, introducing improved forage germplasm had the largest effect. Grass germplasm exhibited on average three times higher herbage yield than the local control, followed by herbaceous legumes with almost doubling herbage productivity, and dual-purpose legumes with 27% higher yield (Fig. 5a). Fertilizer application and planting method increased average herbage productivity by 21% and 7%, respectively (Fig. 5b). Associating a forage grass with a legume increased average total herbage productivity by 49% and almost doubled CP content of the overall forage when compared with a grass only, while ME remained almost equal (Fig. 5c).

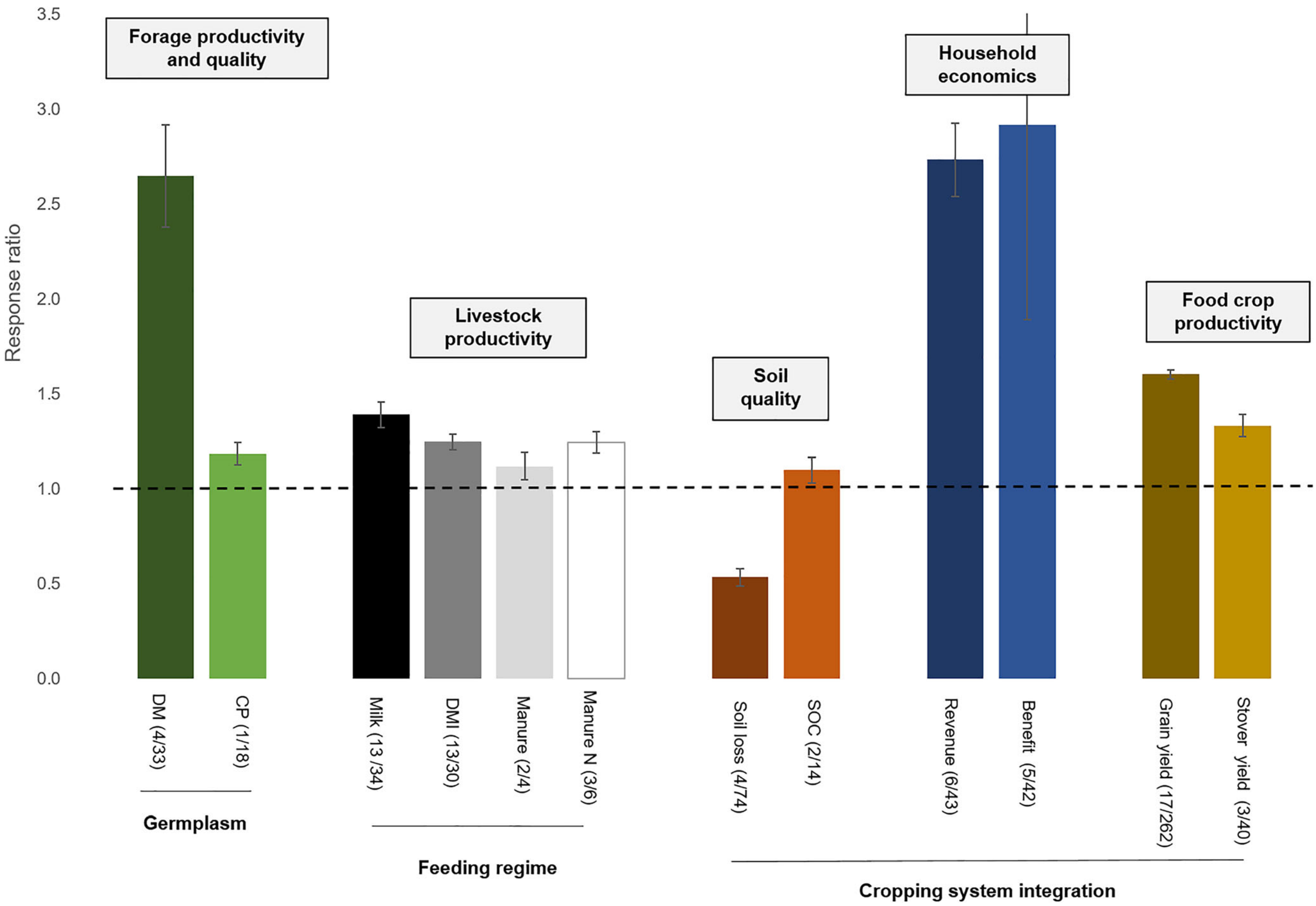

Fig. 4 Weighed mean response ratios with standard error for overall effects of technologies on indicators across the five impact dimensions. Mean effects of improved germplasm on forage productivity and quality (green shades), improved feeding regime on livestock productivity (grey shades), improved cropping system integration on soil quality (red shades), household economics (blue shades), and food crop productivity (brown shades). The dashed line indicates a response ratio of 1, which is the threshold for increase (> 1) or decrease (< 1) when compared with the control. Number of studies and observations are reported in brackets

Impacts of improved feeding regimes with forages on livestock productivity were measured and reported by 72 observations, all focusing on legume interventions (Fig. 3). Overall, they improved milk yield by an average of 39%, dry matter intake (DMI) by 25%, nitrogen content of manure by 24%, and manure quantity by 12% when compared with the basal diets (Fig. 4). When separating impacts by technology subgroups, herbaceous legumes had the largest average effect on milk yield, increasing productivity by 47%. Herbaceous legumes also had the largest effect on DMI, higher than dual-purpose legumes or multipurpose trees and shrubs (Fig. 5d).

Studies also measured effects of tropical forages on soil quality, household economics, and food crop productivity. A total of 88 observations reported effects of forage integration in cropping systems on soil quality, 85 observations on household economics, and 302 observations on food crop yields (Fig. 3). Integrating planted forages into cropping systems overall almost halved soil loss, and increased SOC by an average of 10%. On average, they almost tripled economic revenue and benefit, and increased crop grain yields by 60% and stover yields by 33% (Fig. 4). When separating impacts by technology subgroups, it becomes apparent that associating a forage grass or legume with a food crop was more profitable than hedgerow cropping, more than tripling economic benefit and resulted in 75% higher food crop yields (Fig. 5c).

Improved forage grasses can fill persistent feed gaps in terms of quantity more easily than forage legumes. Overall, forage grasses have been a more important research area than fodder legumes in Africa in the past 100 years (Boonman 1993; Lenné and Wood 2004). However, in many rainfed smallholder farming systems, it is not only the quantity and quality of forage produced that matter, but particularly their seasonality. Especially in drier areas, dry-season feed availability can become more important than overall herbage production (Ates et al. 2018). Relative dry-season feed productivity still remains understudied despite its widely recognized importance.

Changes in milk production are an often-measured response to feed improvements. Dairy animals are frequently used to assess improved forage quality as it translates rapidly

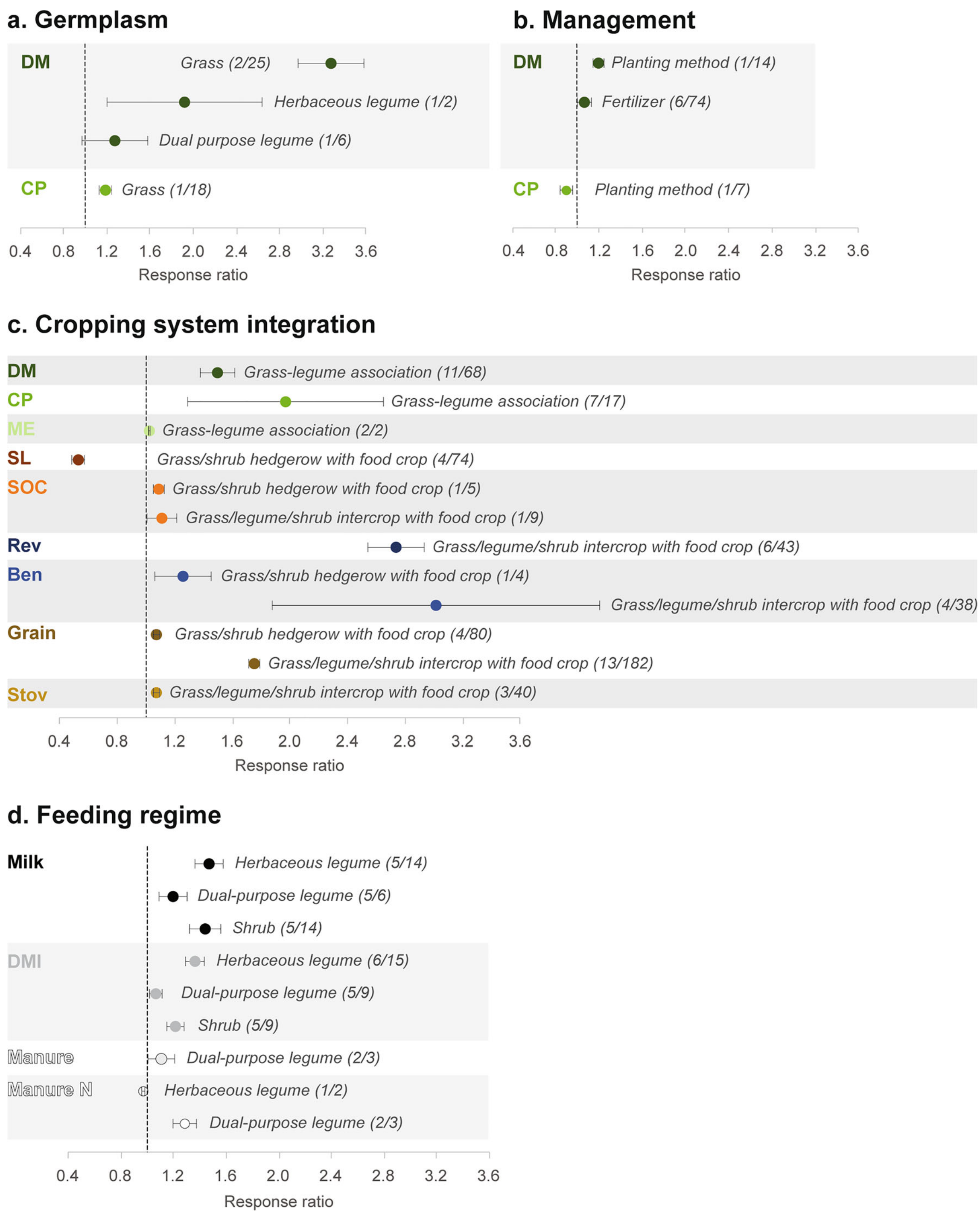

Fig. 5 Weighed mean response ratios with standard error for effects of technology subgroups on indicators across the five impact dimensions. Germplasm subtechnology effects on forage productivity and quality (**a**), management sub-technology effects on forage productivity and quality (**b**), cropping system integration subtechnology effects on soil quality, household economics and food crop productivity (**c**), and feeding regime sub-technology effects on livestock productivity (**d**). Color shades are used to indicate impact dimensions: green for forage productivity and quality, grey for livestock productivity, red for soil quality, blue for household economics and brown for food crop productivity. The dashed line demarcates a response ratio of 1, which is the threshold for increase (> 1) or decrease (< 1) when compared with the control. Number of studies and observations are reported in brackets

into higher milk yield as long as the cows have sufficient genetic potential (Lascano 2001). However, costs of feeding trials involving animals are more resource-intensive to conduct, partly explaining the relatively lower amount of observations on livestock productivity impacts when compared with other impact dimensions. The lower magnitude of impacts from livestock feeding regimes when compared with forage productivity points to the fact that higher quantity and quality of feed does not directly translate into livestock productivity response as several other factors such as current nutritional status of the animals, animal health, breed, and management practices might be limiting productivity. A combination of interventions is often necessary, including improved animal breeds, husbandry, and health to reach desired productivity responses (Van De Ven et al. 2003).

Forage integration into cropping systems has often been highlighted as key to deliver multiple benefits to farmers, yet there are only few successful and published examples (Maass et al. 2015; Paul et al. 2020). Various studies focused on *Desmodium* spp. and mostly referred to the push-pull system in which the pest control factor has an additional effect on food crop yields (Hassanali et al. 2008a). Hedgerow cropping with fodder shrubs could lead to competition and lower food crop yields, depending on the exact agronomic arrangement and agroecological conditions. Variability was high in the economic data, which was also reported by Franzel et al. (2014) for fodder shrub hedgerow cropping. Net return in Kenya and Uganda varied widely, depending on the number of trees grown on the farm, the amount of supplementation with leaf meal, and the milk prices, which can vary between locations and seasons and influence profitability. Inconsistent valuation methods and assumptions further complicated the economic comparisons, e.g., full costs are often not reported, which corroborates with findings by White et al. (2013).

The analysis suggests that tropical forages can deliver multiple benefits to smallholder farmers, although few studies investigated multiple effects simultaneously. Planted forages are uniquely positioned at a crossroads between various disciplines—agronomy, animal nutrition, and environmental sciences—linking crop, livestock, and soil components of farming systems (Paul et al. 2020). Understanding whole system implications of forage introduction into a farming system is required—e.g., for estimating trade-offs in labor requirement or food security when intensifying livestock production (Ates et al. 2018; Paul et al. 2020). In fact, farmers seem to make decisions based on balancing or satisfying multiple objectives, instead of optimizing one single objective—which has been coined “satisficing behavior” (van Kooten et al. 1986; Simon 1957). Farming systems research and whole-farm economic analysis to evaluate benefits and risks, can provide decision support to farmers as well as evidence for researchers and funding agencies to prioritize (research) investments (Pengelly et al. 2003). There is a need for more comprehensive, multidisciplinary studies taking farming system approaches to assess the attractiveness of multiple benefits of forage technologies, depending on specific locations, opportunities, production objectives, and constraints.

3.3 Variability of forage productivity

Lastly, this review aimed to assess and present the variability of forage agronomy data. Absolute forage grass yield figures across studies were highly variable (Table 2). Herbage DM yields for *Pennisetum purpureum* ranged from 0.25 to 37.3 t/ha with most values around 3–10 t/ha, with the lowest value recorded in a semiarid environment per season. Crude protein contents for *Pennisetum purpureum* reached as much as 16.3% in an experiment in Kitale, Kenya, while most other figures varied between 5 and 8% (Table 2).

The high variability in forage agronomic performance in terms of biomass productivity is remarkable which might be explained by two reasons. Firstly, Napier grass is native to SSA and adapted to a wide range of soil and agroecological conditions from 0 to 2100 m above sea level, as well as annual rainfall between 750 and 2500 mm (Negawo et al. 2017). However, yields can vary widely, depending on the cultivar grown, and its interactions with agroclimatic conditions and management. Globally, some studies have even reported yields of up to 66 t DM/ha/year in Malaysia, 78 t DM/ha/year in Brazil or 90 t DM/ha/year in Zimbabwe (Negawo et al. 2017), which is significantly more than the ranges reported for SSA in this review. Similarly, the CP content of Napier grass is significantly influenced by cutting treatments and intervals, and fertilization (Negawo et al. 2017). The choice of experimental control and fertilization regime might also explain some of the observed variability. Secondly, despite various international efforts (e.g., Tarawali et al. 1995; ’t Mannetje 2000), the research field and methods of forage agronomy are not standardized, also due to the comparably less research that has taken place as compared to food crops. Forage biomass productivity is assessed in various ways in terms of establishment time, cutting interval, cutting height, and reporting times (per harvest, season, year). This made results less comparable across sites and studies.

There is a need in SSA for implementing both proposed standards in forage agronomy, and capacity building in forage agronomy. However, investment in forage research has been low, with for example only seven forage agronomists out of the 545 agricultural scientists in Kenya (Murithi and Minayo 2011). Further statistical analysis of the heterogeneity of forage productivity data could identify explanatory variables for the observed site-year variability, relying on additional metaanalysis methods such as random-effects models and sensitivity analysis as proposed by Philibert et al. (2012). Moreover, crop yields observed in studies under controlled conditions, such as on-station experimental trials, are likely greater than those obtained in uncontrolled on-farm situations where the interplay of factors determines yields. It is well

Table 2 Forage grass biomass yields and crude protein contents for *Pennisetum purpureum, Brachiaria spp*. and *Panicum maximum*. The scientific names of the grasses under which the studies were published are used despite recent name changes (*Brachiaria spp* to *Urochloa spp*., *Pennisetum purpureum* to *Cenchrus purpureus*, and *Panicum maximum* to *Megathyrsus maximus*) following Cook and Schultze-Kraft (2015)

Reference	Country	Site	Improved forage crop	Herbage yield	Unit herbage	CP content (% of DM)	Unit CP
Barahenda et al. 2007	Rwanda	Huye	*Pennisetum purpureum*	15.3	t DM/ha/16 months		
Kabirizi et al. 2013	Uganda	Masaka	*Pennisetum purpureum*	10.35	t DM/ha/24 months	7	% of DM
Kabirizi et al. 2015	Uganda	Masaka	*Pennisetum purpureum*	10.35	t DM/ha/year	7	% of DM
Kabirizi 2009	Uganda	Masaka	*Pennisetum purpureum*	10.02	t DM/ha/year	7.4	% of DM
Katuromunda et al. 2011	Uganda	Makerere	*Pennisetum purpureum*	5.61	t/ha		
Kawube et al. 2014	Uganda	Namulonge	*Pennisetum purpureum*	4.03	t		
Kawube et al. 2014	Uganda	Namulonge	*Pennisetum purpureum*	3.65–6.28	t		
Mureithi and Thorpe, 2000	Kenya	Mtwapa	*Pennisetum purpureum*	26.2	t DM/ha/year		
Muyekho et al. 2000	Kenya	Moiben	*Pennisetum purpureum*	5.6–10.8	t DM/ha/year	11.5	% of DM
Muyekho et al. 2000	Kenya	Kitale	*Pennisetum purpureum*	22.9–37.3	t DM/ha/year	16.3	% of DM
Niang et al. 1998	Rwanda	Bubereka	*Pennisetum purpureum*	26.7	kg DM/m/48 months	11.3	% of DM
Njarui 2007	Kenya	Katumani	*Pennisetum purpureum*	0.25–4.35	t DM/ha/season		
Ruto et al. 2000	Kenya	Keiyo	*Pennisetum purpureum*	8.2	t DM/ha/4 cuts		
Mutimura and Everson 2012	Rwanda	Bugesera	*Brachiaria brizantha* cultivars	4.58–5.71	t DM/ha/harvest	4.92–6.41	% of DM
Mutimura and Everson 2012	Rwanda	Bugesera	*Brachiaria decumbens* cultivars	4.79–5.61	t DM/ha/harvest	6.69–7.74	% of DM
Mutimura and Everson 2012	Rwanda	Bugesera	*Brachiaria* hybrids	2.63–5.13	t DM/ha/harvest	4.34–8.91	% of DM
Mutimura and Everson 2012	Rwanda	Nyamagabe	*Brachiaria brizantha* cultivars	4.18–4.47	t DM/ha/harvest		
Mutimura and Everson 2012	Rwanda	Nyamagabe	*Brachiaria decumbens* cultivars	3.72–4.57	t DM/ha/harvest		
Mutimura and Everson 2012	Rwanda	Nyamagabe	*Brachiaria* hybrids	1.32 - 5.95	t DM/ha/harvest		
Njwe et al. 1992	Cameroon	Dschang	*Brachiaria ruziziensis*	1.79	t DM/ha/year	113	kg/ha
Njarui 2007	Kenya	Katumani	*Panicum maximum*	0.15–5.62	t DM/ha/season		

documented that only a small proportion of farmers will reach the average yield under on-station experimentation, owing to the large variability of agro-ecological conditions and management that affect performance. New statistical methods can help to further understand the high on-farm agronomic variability (Vanlauwe et al. 2016).

4 Conclusions

Quantitative reviews are key to summarizing evidence on what is known, synthesizing it for use within or outside of the research domain, and formulating future research priorities. To the best of our knowledge, this review for the first time: (i) takes stock of geographical distribution and forage technologies of past research in SSA; (ii) quantifies the range and magnitude of multidimensional effects of forage technologies including livestock productivity, soil quality, household economics, and food crop productivity; and (iii) presents variability in forage agronomy data.

Major findings of this review include the following: (1) Most studies focused on only one impact dimension, most frequently forage and food crop productivity, and only cropping system integration studies reported benefits across dimensions; (2) Improved forage germplasm had on average 2.65 higher herbage production than local controls, with strongest effect in grasses; (3) Crude protein of the overall forage doubled when grasses and legumes were grown in association; (4) Feeding regimes that include improved leguminous forages increased milk yield by on average 39%, dry matter intake by 25%, and manure production by 24%; (5) When forage technologies were integrated with food crops, soil loss was almost halved, soil organic carbon increased on average by 10%, and grain and stover yields by 60% and 33%, respectively; (6) Variability in the findings from forage agronomy was high.

Further research is needed to explore and explain agronomic variability of forage production. Deployment of additional, statistical metaanalysis techniques could assess site-year variability, and identify relevant explanatory variables (Philibert et al. 2012). Further, it is well-known that agronomic performance and effect sizes may differ between on-station and on-farm experimentation, with the former achieving higher yields due to a variety of factors including better soil quality and management. New statistical methods can help to further understand on-farm agronomic variability, and unravel interactions between genotype, management, and environment effects (Vanlauwe et al. 2016). Such understanding is also needed to inform technology dissemination to ensure higher and more stable performance under heterogeneous smallholder production environments.

Tropical forages can deliver multiple benefits to smallholder farmers, especially when integrated into cropping systems. Therefore, they can play a central role in sustainably intensifying crop-livestock systems in SSA, which has been suggested before (e.g., Ates et al. 2018). Multidimensional impacts of technologies become increasingly recognized as key, also for integration in farming systems and adoption. For example, in the discussions around Climate-Smart Agriculture (CSA) and Sustainable Intensification (SI), concepts of synergies and tradeoffs between various objectives become more and more important (Campbell et al. 2014). Satisfying such multidimensional objectives simultaneously is also suggested to be key to farmers' adoption of technologies (van Kooten et al. 1986; Simon et al. 1957). Adoption of tropical forage technologies, and underlying drivers and barriers, and incentives and enabling environment required to achieve impact at scale, deserves accelerated research attention. Tropical forages are an excellent case to explore and demonstrate the crucial need for multidisciplinary research on multidimensional impacts and tradeoffs technologies that are key to advance mixed crop-livestock systems (Paul et al. 2020). There is a need for more comprehensive, multidisciplinary studies taking farming system approaches to assess the attractiveness of multiple benefits of forage technologies, depending on specific locations, opportunities, production objectives, and constraints.

Results from this study can guide development priority setting and investments by synthesizing and taking stock of past research. They can inform the design of development programs, prioritizing technologies proven successful for dissemination in the region, and indicating magnitudes of impacts that could be expected from the interventions.

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Data availability Data will be published on Harvard Dataverse.

Compliance with ethical standards

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

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