A Qualitative Evaluation of CSA Options in Mixed Crop-Livestock Systems in Developing Countries

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Abstract The mixed crop-livestock systems of the developing world will become increasingly important for meeting the food security challenges of the coming decades. The synergies and trade-offs between food security, adaptation, and mitigation objectives are not well studied, however. Comprehensive evaluations of the costs and benefits, and the synergies and trade-offs, of different options in developing-country mixed systems do not exist as yet. Here we summarise what we know about the climate smartness of different alternatives in the mixed crop-livestock systems in developing countries, based on published literature supplemented by a survey of experts. We discuss constraints to the uptake of different interventions and the potential for their adoption, and highlight some of the technical and policy implications of current knowledge and knowledge gaps.

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1 Background and Methods

Mixed crop-livestock systems, in which crops and livestock are raised on the same farm, are the backbone of smallholder production in the developing countries of the tropics (Herrero et al. 2010). It is estimated that they cover 2.5 billion hectares of land globally, of which 1.1 billion hectares are rainfed arable lands, 0.2 billion hectares are irrigated croplands, and 1.2 billion hectares are grasslands (de Haan et al. 1997). Mixed crop-livestock systems produce over 90 per cent of the world's milk supply and 80 per cent of the meat from ruminants (Herrero et al. 2013). They occur in nearly all agro-ecological zones in developing countries, with an enormous variety of climatic and soil conditions. The location of the mixed systems in the global tropics and subtropics is shown in Fig. 1. The mixed systems are those in which more than 10% of the dry matter fed to animals comes from crop by-products or stubble, or more than 10% of the total value of production comes from non-livestock farming activities (Seré and Steinfeld 1996). Rather than break the mixed systems down further in terms of whether they are rainfed or irrigated and on the basis of temperature and length of growing period (LGP), as in Robinson et al. (2011), Fig. 1 uses the breakdown in Herrero et al. (2009) on the basis of whether the mixed systems are "extensive", with lower agroecological potential (LGP < 180 days per year), or "intensifying", with higher agroecological potential (LGP > = 180 days per year) coupled with better access to urban markets (<8 hours' travel time to urban centres with a population > 250,000).

In both Latin America and sub-Saharan Africa (SSA) the great majority of the mixed systems are rain-fed. In Asia, a large proportion of the mixed systems are irrigated. The mixed systems extend to the tropical highlands of Latin America, East and southern Africa and northern Asia. In well-integrated crop-livestock systems, livestock provide draft power to cultivate the land and manure to fertilize the soil, and crop residues are a key feed resource for livestock. These mixed systems currently provide most of the staples consumed by many millions of poor people in the global tropics: between 41 and 86 per cent of the maize, rice, sorghum and millet, and 75 per cent of the milk and 60 per cent of the meat (Herrero et al. 2010). The mixed systems will be critically important for future food security too. Human population may peak in Asia and Latin America soon after 2050, but growth is projected in Africa until well into the twenty-second century, and some of this growth will occur not only in urban areas but also in the rural-based mixed systems, where more than 60% of people already live (Herrero et al. 2010).

The justification for integrating crop and livestock activities is that crop (or livestock) production can produce resources that can be used to benefit livestock (or crop) production, leading to greater farm efficiency, productivity or sustainability (Sumberg 2003). Optimal interactions between different operations on the farm can increase farmer's incomes, as well as system-wide resilience and environmental sustainability (Descheemaeker et al. 2010). With limited access to agricultural inputs, combining crops with livestock also offers complementary benefits to each that would otherwise require external inputs to maintain. These resources can be in

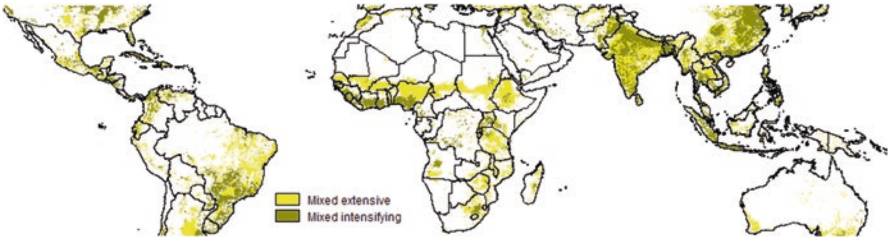

Fig. 1 Mixed crop-livestock systems in the tropics and subtropics (from Herrero et al. 2009). Mixed systems (M): those in which >10% of the dry matter fed to animals comes from crop by-products or stubble, or >10% of the total value of production comes from non-livestock farming activities. Original classification of Seré and Steinfeld (1995). Mixed systems broken down into "extensive", LGP < 180 days per year (lower agronomic potential), and "mixed intensifying", LGP > 180 days per year (higher agronomic potential) plus better market access (<8 h travel time to an urban centre with >250,000 people)

the form of feed biomass such as crop residues, animal manure, draught power, and cash. Resource-poor farmers depend directly on the food production system for livelihood security, and thus, mixed systems offer key livelihood diversification options, as smallholders in developing countries aim to minimise risk associated with agricultural production, liquidity constraints, high transaction costs, that can all result in income and consumption fluctuations (Dercon 1996; Davies et al. 2009; Barrett et al. 2001).

The future of mixed crop-livestock systems in developing countries is a subject of ongoing debate. On the one hand, they have been seen as one stage in an evolutionary process of intensification via increasing human population pressure on a relatively fixed land resource (Boserup 1965). Intensification dynamics may lead to land consolidation and the exiting of some producers from agriculture altogether (e.g., Australia and North America); or it may lead to exchanges and market-mediated interactions between different producers who may be widely separated geographically (e.g., parts of Asia). On the other hand, structural constraints may continue to impede both adoption of intensification technology and land consolidation in smallholder farming (Waithaka et al. 2006; Fritz et al. 2015). Possibilities for sustainably intensifying production and productivity in many parts of SSA (in particular) are likely to remain severely constrained well into the future. The impacts of climate change on smallholder mixed systems will constitute an additional, and in places severe, challenge in the future (Thornton and Herrero 2015).

Despite the adaptation challenge, the mixed systems could play a critical role in mitigating greenhouse gases from the agriculture, forestry and land-use sectors. Mixed crop-livestock systems are a considerable source of greenhouse gas (GHG) emissions, accounting for 63% of the emissions from ruminants globally (Herrero et al. 2013). Even so, the emissions intensities (the amount of greenhouse gases emitted per kg of meat or milk) of the mixed systems are 24–37% lower than those of grazing systems in Africa (Herrero et al. 2013), mostly because of the higher-quality diets of ruminants in the former compared with the latter systems. The mixed systems also provide 15% of the nitrogen inputs for crop production via manure amendments (Liu et al. 2010). Carbon sequestration in soils and biomass provides another mitigation opportunity in the mixed systems (Seebauer 2014).

The mixed systems have considerable potential for addressing the three pillars of Climate Smart Agriculture (CSA), namely production for food security, adaptation, and mitigation. The synergies and trade-offs between these three, however, are not well studied, particularly in the mixed systems regarding the effects of climate change on livestock and on crop-livestock interactions in a smallholder context (Thornton and Herrero 2015). Quantifying the baseline situation as well as the effects of different alternatives on the various dimensions of climate smartness in different contexts are needed before robust statements can be made about what is and what is not “climate smarter” than current practice.

Mixed crop-livestock systems offer a wide range of possibilities for adapting to climate change and mitigating the contribution of crop and livestock production to GHG emissions. This is in large part the result of the interactions between crop and livestock enterprises that may be able to be exploited to raise productivity and increase resource use efficiency, increasing household incomes and securing availability and access to food (Thornton and Herrero 2015). Integration of crops and livestock can reduce resource depletion and environmental fluxes to the atmosphere and hydrosphere, it can result in more diversified landscapes that favour biodiversity, and it can increase the flexibility of the farming system to manage socio-economic and climate variability (Lemaire et al. 2014). Integration also reduces the risk of smallholders who are often vulnerable not only to crop failure and climate change, but also to other risks such as agricultural trade risk, and food price risk, as well as health and demographic risks (Devereux 2001).

Mixed farming systems have various characteristics that may be advantageous in some situations and disadvantageous in others (and sometimes both in the same situation) (van Keulen and Schiere 2004). For example, the use of draught power allows larger areas of land to be cultivated and it allows more rapid planting when conditions are appropriate. On the other hand, this may mean that extra labour (often women’s) is required for weeding. On a mixed farm, crop residues can be mulched, thereby helping to control weeds and conserve water; and they are an alternative source of low-quality roughage for livestock. But again, feeding crop residues may compete with other uses of such material, such as mulching, construction, and nutrient cycling. A major constraint to increased crop-livestock integration is that it can be complex to operate and manage (van Keulen and Schiere 2004; Russelle et al. 2007). Nonetheless, this integration is critical for smallholders in order to increase livelihood security while reducing vulnerability to food insecurity, as well as to climate change.

Comprehensive evaluations of the costs and benefits, and the synergies and trade-offs, of different options in developing-country mixed systems do not exist as yet. The question this chapter seeks to answer is, what can presently be said about the climate smartness of different alternatives in the mixed crop-livestock systems in developing countries, from both a technical and an institutional perspective? We build on the listing in FAO (2013) of crop and livestock management interventions that may be able to deliver multiple benefits (food security and improved climate change mitigation and adaptation) in different situations. These span the range of crop and grazing land management, water management, and livestock management, and include options related to food storage and processing, insurance, and use of weather information. Many of these alternatives have far wider geographic applicability and are not limited just to the mixed systems of the developing world.

The methods used here to evaluate how farm-level CSA management practices and technologies affect food production, adaptive capacity and climate change mitigation in mixed farming systems are based on the protocol of Rosenstock et al. (2016), supplemented by a survey of experts. We evaluated their responses through an informal survey. CSA experts were asked to identify the effects of each intervention on indicators of CSA (as in Rosenstock et al. 2016) in relation to food production (e.g., yield and income effects), resilience (e.g., effects on quality of soil resources, resource use efficiency, labour requirements), and mitigation (e.g., effects on emissions and emission intensities). Additional, the survey gathered information regarding key climate risks that each potential CSA practice addresses as well and identified socioeconomic conditions that enhance the practice. The results from this survey were averaged to determine whether the practice had a positive (+), negative (−), or undetermined (+/−) impact on the key CSA indicators noted above, such as carbon sequestration.

The next section contains descriptions and brief evaluations of the CSA interventions. Section 3 contains brief discussions of constraints to the uptake of these interventions and the potential for their adoption. In Sect. 4 we highlight some of the technical and policy implications of current knowledge as well as knowledge gaps concerning CSA interventions in the mixed crop-livestock systems of developing countries.

2 CSA Interventions in the Mixed Systems

Climate-smart options for mixed crop-livestock system vary widely in their potential impacts on agricultural productivity, climate change resilience, and GHG mitigation (Table 1). While experts agree that most options will improve productivity, impacts on resilience and mitigation are particularly variable. This variability is due in part to context specificity in the effect of a particular intervention. For some of the interventions, the strength of evidence to support the assessments is very limited. In the following subsections, we unpack the potential trade-offs, context-specificity, and constraints to adoption for each CSA option for mixed crop-livestock systems.

2.1 Changing Crop Varieties

Decades of research has gone into developing crop varieties that can improve agricultural productivity and resilience by increasing yield, reducing the time for crops to mature, increasing tolerance to stresses such as drought, salinity, pests, and disease, and improving the nutritional quality of crops. Without such innovations, it is

Table 1 Climate-smart options available to smallholders in mixed crop-livestock systems in developing countries: potential impacts and strength of evidence. Scoring based on authors' assessment of the articles found in a systematic review of CSA (described in Rosenstock et al. 2016), supplemented with a survey of nine experts through an informal survey

Options	Potential impacts			Strength of evidence	Selected examples
	Prod.	Res.	Mit.		
Change crop varieties	+	+/−	+/−	***	Krouma 2010, Kumar et al. 2008, Kamara et al. 2003
Change crops	+	+	+/−	*	Sauerborn et al. 2000
Crop residue management	+/−	+	−	**	Liu et al. 2003, Mrabet 2000, Obalum et al. 2011, Omer et al. 1997, Sissoko et al. 2013
Crop management	+	+/−	+/−	*	Wang et al. 2006, Borgemeister et al. 1998
Nutrient management	+	+	+	***	Surekha et al. 2010, Szilas et al. 2007, Torres et al. 1995, Witt et al. 2000, Yadav and Tarafdar 2012
Soil management	+	+	+/−	**	Kywe et al. 2008, Yang et al. 2010, Yusuf et al. 2009, Zougmore et al. 2000, Suriyakup et al. 2007
Change livestock breed	+	+	+	*	Thornton and Herrero 2010
Manure management	+	+/−	+/−	*	Rabary et al. 2008, Salako et al. 2007, Srinivasarao et al. 2012, Taddesse et al. 2003
Change livestock species	+	+/−	+/−	*	Limited information; discussed by Hoffmann 2010; FAO 2013
Improved feeding	+	+/−	+/−	**	Akinlade et al. 2003, Akinleye et al. 2012, Barman and Rai 2008, Kaitho et al. 1998, Lallo and Garcia 1994; Thornton and Herrero 2010
Grazing management	+	+	+/−	**	Bozkurt and Kaya 2011, Moyo et al. 2011, Mattiauda et al. 2013, Ma et al. 2014
Alter integration within the system	+	+	+	*	Tuwei et al. 2003, Kaitho et al. 1998
Water use efficiency and management	+	+	+/−	**	Kipkorir et al. 2002, Li et al. 2004, Mahmoodi 2008, Mailhol et al. 2004, Speelman et al. 2008
Food storage	+	+	+	*	Sadfi et al. 2002, Haile 2006, Ilboudo et al. 2010, Koona et al. 2007
Food processing	+	+/−		*	Mahmutoğlu et al. 1996
Use of weather information	+	+	+/−	−	Hansen et al. 2011
Weather-index insurance	+	+/−	+/−	*	Cole et al. 2012

The results from this survey were averaged to determine whether the practice had a positive (+), negative (−), or undetermined (+/−) impact on the key CSA indicators. Potential impacts (prod = production, res = resilience, mit = mitigation): + = positive, − = negative, +/− = uncertain. Strength of evidence: ***= confident, **likely, *poor, − speculation thought that crop yield in developing countries would be 20–24% lower than current levels, 6–8% more children would be undernourished, and per capita calorie consumption would be 14% lower than current levels (Evanson and Gollin 2003). Adaptation strategies such as improved varieties may reduce projected yield losses under climate change, particularly among rice and wheat in the tropics (Challinor et al. 2014). High yielding varieties can improve the food self-sufficiency of smallholders and increase income without needing to cultivate extra land. Drought-tolerant varieties have helped to stabilize yields, particularly of cereal crops in rain-fed systems (La Rovere et al. 2014). As drought, pest and disease outbreaks, and water salinization become more common with climate change and increasing demands on natural resources, changing crop varieties will continue to be among the first lines of defence for improving productivity and resilience in mixed crop-livestock systems. However, research on crop improvement and resilience has been limited to staple grains for the most part. Within mixed systems, a diverse number of crops including feed and forage species as well as trees or fodder shrubs contribute to the resilience of the system. More attention is needed to understand how the climate resilience of non-traditional products that contribute to smallholder health and nutrition and overall system performance can be enhanced.

Adoption rates of improved varieties and seeds in areas where those seeds are available and awareness is high can be as much as 85% among smallholder farmers (e.g., see Kyazze and Kristjanson 2011). That study showed that high-yielding varieties have the greatest appeal among smallholder farmers, followed by tolerance to drought and pests. However, recent evidence shows that very few farmers actually have access to improved crop varieties or improved seeds in the developing world. In SSA, 68–97% of seed grown by smallholder farmers comes from informal sources (i.e. seed saving, friends and relatives) and local markets (McGuire and Sperling 2015). Thus a primary barrier to adoption of improved varieties is availability of seeds (Westermann et al. 2015).

2.2 Changing Crops

Under climate change, the suitable area for cultivation of most staple crops in the tropics is likely to both shift and decrease, requiring farmers to adopt transformative types of adaptation, such as switching crops (Vermeulen et al. 2013). Maize, beans, banana, and finger millet, staple crops in much of SSA, could experience reduction in suitable areas for cropping by 30–50% (Ramirez-Villegas and Thornton 2015). Changing from less suitable crops to those more suitable in future climates is an effective strategy for maintaining productivity and increasing resilience to climate change. While many studies have looked at climate impacts on staples, information on the likely impacts of climate change on forages such as Napier grass that are typically used in mixed systems is practically non-existent. In areas that are projected to see improvements in crop suitability, such as a relaxation of current cold temperature constraints in parts of the tropical highlands in East Africa, for example, mixed crop-livestock farmers may be able to capitalise by planting crops appropriate to the changing climatic conditions.

While changing crops is a more substantial alteration to a mixed crop-livestock system than simply changing varieties, adoption rates of new crops and switching crops can still be quite high compared with other management practices. In Rakai, Uganda, for example, more than a quarter of surveyed smallholder farmers had introduced a new crop in the last 10 years, whereas more than a third of households had also stopped growing a crop that was no longer seen as profitable or suitable (Kyazze and Kristjanson 2011). However, in many cases the potential to change crop species will depend on the familiarity of farmers with the new species as well as cultural preferences. Barring potentially catastrophic losses (such as the introduction of maize lethal necrosis diseases in Kenya in 2013), the transition to new crops is likely to be a gradual and relatively slow process.

2.3 Crop Residue Management

Crop residue management practices determine the destination and use of stover and other crop byproducts. Some effective residue management solutions retain plant residues and practices that minimally disturb the soil. In addition to potential increases in soil organic carbon and subsequently increased water infiltration and storage within the soil, effective crop residue management can dramatically decrease soil erosion through the protection of the soil surface from rainfall (Lal 1997). Such practices can include minimum or no-tillage, cover cropping, and the addition of mulch. Minimum tillage practices limit disturbance of the soil and therefore protect the soil structure from degradation. Additionally, limiting tillage can decrease soil crust formation. Both of these factors contribute to enhancing water infiltration into the soil and subsequently increase water productivity of agroecosystems (Rockström et al. 2009). Cover cropping includes the growing of typically a non-harvested or partially harvested crop either in a crop rotation or in the non-main growing season. Cover cropping with leguminous crops can be very beneficial to typically low-fertility and highly weathered soils common in smallholder systems (Snapp et al. 2005). Similar to both minimum tillage and cover cropping, mulching can increase soil aggregation (Mulumba and Lal 2008), and thus soil physical quality. In addition, the use of mulching also protects soils from direct impact by rainfall, greatly reducing nutrients and organic matter lost through soil erosion (Barton et al. 2004).

Minimum tillage practices must be adapted to local conditions and must contain strong incentives for farmer adoption. A study in Central Kenya found that profitability and yield depend on the soil fertility status (low, medium, high), with neither tillage nor crop residue retention practices being profitable (Guto et al. 2012). While cover crops offer great potential, there are costs that must be weighed by potential adopters. Cover cropping can potentially interfere with subsequent crops by using finite soil water, they can decrease soil warming, subsequently inhibiting seed germination, and increasing the direct cost and production risks to farmers (Snapp et al.

2005). Current practices of grazing livestock on harvested fields (and other free grazing practices) would need to be addressed at the same time, and there may also be implications for women's labour requirements, for example. Increased soil degradation and subsequent loss of crop yield can result from this practice (Udo et al. 2011). Many smallholder agroecosystems already have a high demand for crop biomass for feed and fuel. Areas where mulching has higher adoption potential are those where increased biomass production is high enough to meet feed, fuel, and mulching requirements (Valbuena et al. 2012).

2.4 Crop Management

Crop management techniques within the perspective of climate change range widely and include practices such as modifying planting date and multicropping with multiple crops and varieties. As the world climate system changes, local weather patterns will become more unpredictable. In addition to accessing available weather forecasting information, farmers will need to adjust planting seasons accordingly. Changes in planting dates can have profound impacts on farm productivity. A study in Zimbabwe found that delayed planting results in a 32% loss of grain yield (Shumba et al. 1992). However, in order for some farmers to effectively plant earlier might require adjusting cultivation practices. In the same study, Shumba et al. (1992) reported that earlier planting was only feasible with the use of select pesticides and minimum tillage techniques. Multicropping involves the growing of multiple crops within the same growing season—and can include intercropping (within the same field at the same time) with both leguminous and non-leguminous crops and trees (agroforestry). Intercropping—the planting of two or more crops on the same field within one season—has profound effects on the ability of smallholder farmers to reduce risk. Crops in intercropping systems typically access different soil water and nutrient resources, have difference water requirements, and have varying growth and maturity rates, all of which reduce the risk of total crop failure (and the associated risk of food insecurity) due to erratic or decreased precipitation (Ghosh et al. 2006). An extensive analysis reported that monocropping—the most common agricultural practice in Africa—is the most susceptible to the negative effects of climate change (Nhemachena and Rashid 2008).

While changing planting date for many crops in some areas might be very simple, a study of the Nile Basin in Ethiopia indicated that lack of access to weather information and extension services is a formidable constraint to changing planting dates (Deressa et al. 2009). Even with access to these services, farmers will require time to test planting dates before adoption, or more likely, adjustments might need to be made on a season-by-season basis. Additionally, changes in planting and harvest dates might require changes in cultivation practices as well as changes in market systems. In some situations, labour availability may become an issue – for instance, when children are in school and cannot help with weeding. With respect to intercropping, determining the proper crop combinations and intercropping type requires both local knowledge and evaluation. The use of intercropping systems can also increase labour demands as some intercropped plants will require varying weeding, applications, and harvest times (Rusinamhodzi et al. 2012).

2.5 Nutrient Management

Smallholders manage complex nutrient cycles on mixed crop-livestock farms (Tittonell et al. 2009) offering multiple opportunities to become more climate-smart. Producers control the distribution of nutrients through the same means as mono-specific growers and ranchers such as the application of inorganic and organic fertilizers and composts, growing trees, recycling of wastes, and improving animal diets which all have known benefits for improving productivity, water and nutrient use efficiency, and reducing GHG intensity of production (Kimaro et al. 2015; Barton et al. 2004; Zingore et al. 2007). A key feature of nutrient management in mixed farming is that farmers transfer nutrient-rich materials – manure, residues, feeds – between production activities. Technological change for any specific subcomponent of the system, therefore, has cascading affects across the farm because of concomitant changes in nutrient availability (van Wijk et al. 2009). The consequence is that individual management changes can create either trade-offs or synergies not only within, but also among, farm subcomponents and products. For example, conservation agriculture is often promoted in mixed crop-livestock systems to help maintain soil chemical and physical properties amongst other CSA-relevant goals (for example, water-use efficiency and soil carbon sequestration). However, crop residues in mixed systems are typically fed to livestock, often serving as a vital feed resource during periods of low supply (Giller et al. 2015). Thus, conserving crop residues for fertility may reduce nutrients available for other subcomponents of the system.

At this time, much is known about nutrient dynamics of individual subcomponents and entire mixed systems (Abegaz et al. 2007); however, less is understood about how to optimize the various subcomponents to meet multiple objectives (Groot et al. 2012). For example, recycling of manure nutrients back to crop fields is one of the most often cited interventions to improve nutrient management in mixed systems. Closing the nutrient cycle in this way has the potential to increase crop yields (including feed byproducts) and farm output while reducing GHG emissions from stored manures. In practice, however, the efficiency of this practice to preserve the nutrient composition of the manure is highly subject to handling and storage conditions and transfer time, with farmer practice having a significant impact on the final fertilizer value of the material (Rufino et al. 2006). Farmer practice is subject to available resources, materials and labour, and as such utilization of manure nutrients may be impractical when put up against other competing goals of the household. Similar practical challenges obstruct implementation of other nutrient management options; and the use of human waste comes with its own challenges relating to health and cultural acceptability. Mixed system farmers have the opportunity to improve feeding on farms, typically by supplying high protein feeds. Higher protein diets tend to increase productivity of livestock through improved digestibility and intake of crude protein (Bekele et al. 2013) and decrease emissions intensity from milk and meat production (Barton et al. 2004). However, the potential to plant legume species is often constrained by factors as varied as seed availability, access to knowledge, and land rights (Franzel et al. 2014).

2.6 Soil Management

Managing soil resources for climate-related risks often involves increasing soil physical quality while maintaining or improving soil fertility status. Soil physical characteristics important for climate change adaptation include increased soil organic carbon and soil aggregation, and enhancing these properties can lead to increased water infiltration into the soil and subsequently soil water storage for plant use. Additionally, management of soil fertility within smallholder agroecosystems is especially important as climate change is expected to negatively affect soil fertility and the mineral nutrition contained within plants (St Clair and Lynch 2010). These important aspects of soil quality are managed through effective use of crop rotations, leguminous plants, and livestock density management. The use of crop rotations decreases disease incidence, suppresses weed infestation, and can enhance nutrient cycling when leguminous plants are used (Mureithi et al. 2003). Leguminous plants and trees can be effectively incorporated into smallholder agroecosystems through intercropping, relay cropping, and planting boundaries. The nitrogen-fixing capabilities of leguminous plants can increase soil fertility of smallholder soils as well as provide important nutrients to smallholder farmers (Kerr et al. 2007). Livestock stocking management is less straightforward, however. While the determination of livestock density varies by environment and livestock type, Taddesse et al. (2003) reported that medium-stocking intensity can lead to higher species richness compared with both a high-stocking intensity and the non-grazed control, as well as resulting in less soil compaction than the high-stocking intensity treatment. These results may not hold in other situations because of the diverse conditions found in smallholder livestock keeping systems.

While each of these practices represents possible techniques to effectively manage soil resources, each practice must be assessed to identify possible constraints or drawbacks. For example, a study in Tanzania found that adoption of leguminous crop rotations was negatively affected by longer distances from houses to farm plots, smaller plot sizes, and poor fertility soils (Kassie et al. 2013). While leguminous plants offer many benefits to smallholder farmers, farmers are not likely to adopt this practice unless there are clear market returns (Snapp et al. 2002). The effects of livestock grazing management on soil quality is affected by many geographic-specific factors including soil type and topography. Precipitation can also exacerbate the effect of livestock grazing on compaction during heavy rainfall events (Ghosh et al. 2006). Additionally, stocking intensity must be managed in such a way that sufficient crop residue is returned to the soil to maintain nutrient cycling and soil physical quality (de Faccio Carvalho et al. 2010). The ways in which different soil management interventions interact at the systems level in helping to meet food security objectives remain to be elucidated (Hurni et al. 2015).

2.7 Changes in Livestock Breed

The local breeds of cattle that are raised in the developing world are generally well-adapted to their environments in terms of disease resistance, heat tolerance and nutritional demand. Their productivity is often low, however, and the emissions intensity of production (the amount of GHG emissions produced per kilogram of milk and meat) can be high. The utilisation of more productive animals is one strategy that can lead to higher productivity and reduced emissions intensity. Livestock populations exhibit natural genetic variation, and selection within breeds of farm livestock may produce genetic changes in the range 1–3% per year in trait(s) of interest (Smith 1984). Attempts to utilize this genetic variation to breed reduced-emissions cattle, for instance, are inconclusive as yet. Within-breed selection often poses challenges in developing countries because appropriate infrastructure such as performance recording and genetic evaluation schemes are often lacking. Cross-breeding is usually more feasible, and can deliver simultaneous adaptation, food security and mitigation benefits. Locally-adapted breeds can be utilised that are tolerant to heat, poor nutrition and parasites and diseases, and these traits can be transferred to crossbred animals. Cross-breeding coupled with diet intensification can lead to substantial efficiency gains in livestock production and methane output. Crossbred cattle, for example, can easily produce more than double the amount of milk and meat, compared with local breeds (Galukande et al. 2013). Widespread uptake could result in fewer but larger, more productive animals being kept, which would have positive consequences for incomes, methane production and land use. The adoption potential of cross-bred cattle is high: adoption rates of crossbred dairy animals of 29% have been observed in Kenya (Muriuki and Thorpe 2006). The benefits on production are substantial, and the mitigation potential is positive, though relatively modest; for the mixed systems of the tropics and subtropics it is estimated at about 6 Mt. CO_2-eq per year (Thornton and Herrero 2010).

There are significant issues associated with the feasibility of widespread adoption of crossbred animals, however. The adoption rate of crossbreds in Kenya is atypical of developing countries as a whole. There are several reasons for this. Larger, more productive animals need more and higher-quality feed and water, which may have substantial impacts on land and labour resources at the household level. For example, women collect water for animals in many African households when it is not immediately available. Adoption of crossbreds may therefore increase work burden on women. Crossbreds also require some capital investment, and smallholders may have no access to viable lines of credit. A key constraint seems to be an adequate understanding of the objectives and attitudes of smallholders; smallholders have often found breeding programs to be unsuitable, unprofitable, or impossible to implement – this applies to small ruminants as well as to large (Kosgey et al. 2006). In addition, the impacts of an increasingly variable climate on crossbred animal performance may increase household risk in ways that are unacceptable. Some East African livestock keepers, for example, generally prefer dealing with indigenous breeds, especially during times of severe drought, as smaller animals can be physically handled in ways that become impossible with heavier animals (BurnSilver 2009).

2.8 Manure Management

The utilisation of livestock manure to add nutrients back to the soil is one of the key crop-livestock interactions in mixed farming systems. Manure when used as a soil amendment can benefit the soil, resulting in crop production and resilience benefits for smallholders via increased nutrient supply to crops and improved soil structure and water holding capacity, for example. Manure has well-documented impacts on soil chemical and physical properties. For example, Srinivasarao et al. (2012) showed a positive interaction between the application of manure and mineral fertilizer on carbon stocks in the soil in semiarid regions of India, with beneficial effects on crop yield stability. Taddesse et al. (2003) demonstrated positive impacts of manure application in the Ethiopian highlands on pasture biomass production, species richness and water infiltration rates. The GHG emissions dimension associated with manure is complex. When stored, manure can release significant amounts of nitrous oxide and methane. Nitrous oxide and other GHGs are also released when manure is applied to the land (Smith et al. 2008). In tropical mixed farming systems, the opportunities for manure management, treatment and storage are often quite limited, although there may be opportunities in zero-grazing smallholder dairy systems, for example (FAO 2013). In more extensive systems, manure has to be collected from the field, usually once it has dried and methane emissions are negligible (Smith et al. 2008). Various options exist to modify GHG emissions in the production, storage and application of manure. Improved livestock diets and the use of certain feed additives can substantially reduce methane emissions from enteric fermentation and manure storage (FAO 2013). Storage emissions can be reduced by composting the manure or by covering manure heaps; and manure can be digested anaerobically to produce methane as an energy source, for example (Smith et al. 2008). Generally, however, manure storage under anaerobic conditions is only viable in the highly intensive livestock production systems, and anaerobic digestion technology is unlikely to be applicable in smallholder mixed systems for the foreseeable future. Emissions during and after the application of manure to the field can be reduced by rapid incorporation of the manure into the soil (FAO 2013).

These manure management options can all contribute to increased productivity, but the synergies and trade-offs in relation to household resilience and mitigation benefits in different contexts and production systems are not well studied. Their applicability in relatively low-input mixed farming systems is likely to remain limited (FAO 2013), as the investment costs, labour demands and technical know-how will be beyond the reach of the great majority of smallholders. Some recent studies indicate that there is potential for communal biogas digesters to improve soil fertility in the developing world (see, for example, Smith et al. 2014), but the constraints of unaffordability, water scarcity, inappropriate technology and lack of technical capacity may be insuperable without considerable public sector investment (Mwakaje 2008). The conditions under which such interventions are climate smarter are still largely unknown.

2.9 Changes in Livestock Species

The substitution of one species of livestock for another is one strategy that livestock farmers can use to increase their resilience to climatic and economic shocks. There are various mechanisms by which this can occur: risk can be spread by having a more diverse species portfolio, and for a farm with small stock, it will often be easier to shift between small stock species than between larger, less "liquid" stock. The last several decades have seen species substitution in several parts of Africa, as a result of long- and/or short-term climate and vegetation changes. In parts of the Sahel, dromedaries have replaced cattle and goats have replaced sheep, in the wake of the droughts of the 1980s (Hoffmann 2010). In Ethiopia, smallholders are adopting goats and sheep rather than cattle in response to market opportunities: there is strong urban demand for meat, it is easier to sell small animals, and profits accrue more quickly and are generally less risky. Traditional cattle keepers in parts of northern Kenya and southern Ethiopia have adopted camels as part of their livelihood strategy as a result of drought, cattle raiding and epizootics. More widespread adoption of camels and goats in the drylands of Africa is now being observed in many other places – unlike cattle and sheep, browsers feed on shrubs and trees, and browse may be a relatively plentiful feed resource even in situations where herbaceous feed availability is declining. Livestock species substitution may also arise from considerations of GHG emissions, given that there are considerable differences in emissions and emission intensities between ruminant livestock production systems and monogastric systems producing chickens and pigs, for example (Hoffmann 2010).

Livestock species substitution will no doubt continue to occur, and it is clear that these substitutions can deliver various benefits: enhancing resilience, maintaining or increasing productivity in the face of shocks, and mitigating GHG emissions. There is little evidence, however, of how the synergies and trade-offs may play out in the mixed crop-livestock systems, particularly through time: while there may be long-term benefits of species substitution, there are likely to be short-term costs and challenges associated with species switching that smallholders may be unwilling or unable to address (FAO 2013). The challenges revolve around the capital outlays involved, and the lack of technical know-how needed to manage unfamiliar livestock species.

2.10 Improved Feeding

Interventions that target improved feed resources can result in faster animal growth rates, higher milk production, earlier age at first calving, and increased incomes. Better nutrition can also increase fertility rates and reduce mortality rates of calves and mature animals, thus improving animal and herd performance and system resilience to climatic shocks. For cattle, such interventions may include the use of improved pasture and agroforestry species and the use of nutritious diet supplements. Feed availability for ruminants can be a major constraint in the mixed systems of the tropics during the dry season. The options available to smallholders include higher-digestibility crop residues, diet supplementation with grain, small areas of planted legumes ("fodder banks"), the leaves of certain agroforestry species, and grass species that can be planted on field boundaries or in rehabilitated gullies (with added erosion control benefits). These kinds of supplements can substantially increase productivity per animal while also increasing resilience by making substantial impacts on income. For example, the feeding of 1 kg of *Leucaena leucocephala* leaves per animal per day can nearly triple milk yields and live-weight gains (Thornton and Herrero 2010). At the same time, because these supplements improve the diet of ruminant livestock, the amount of methane produced by the animal per kilogram of meat and milk produced is substantially reduced (Bryan et al. 2013). There may also be soil carbon sequestration benefits from planting trees and deep-rooted pasture species. For example, planting *Leucaena* trees on farms increases carbon sequestration in the soil, possibly by up to 38 tonnes of carbon per ha (Albrecht and Kandji 2003). In many regions, crop residues (stover) are a critical feed resource; increases in stover digestibility of 10 percentage points are well within the range of variation in digestibility that has been observed in sorghum, for example (Blümmel and Reddy 2006). Such genetically improved dual-purpose crops (food and feed), both cereals and legumes, are widely grown in some parts of the tropics.

Improving the diets of ruminants is one of the most direct and effective ways of increasing productivity and incomes, while mitigating GHGs at the same time. Mixed crop-livestock system diets are often complex and amenable to modification. Widespread application of the different options above is plausible in many situations. Adoption rates of up to 43% for genetically improved dual-purpose crops have been observed in some parts of West Africa, though lower adoption rates are more usual (Kristjanson et al. 2002).

There may be constraints at the local level, however: diet intensification may require additional household labour, and the availability of appropriate planting material may be inadequate, for example. In addition, some of these alternatives require appropriate technical capacity to manage them as well as some cash investment. Some also require land, although sometimes competition for land can be avoided: in an example from Ethiopia, degraded land is given to female headed households or landless youth, who thus get a chance to produce small stock for sale. Overall, the above constraints may not pose insuperable barriers to the continuing uptake of climate-smarter feeding practices in the future.

2.11 Grazing Management

Native grasses in rangelands and mixed systems are often of relatively low digestibility. The productivity of pastures can be increased through adding nitrogen and phosphorus fertilizers, adjusting the frequency and severity of grazing, changing plant composition, and utilizing irrigation. Improving pasture productivity offers a readily available means of increasing livestock production, particularly in the humid/sub-humid tropics. Substantial improvements in livestock productivity and soil carbon sequestration are possible, as well as reductions in enteric emission intensities, by replacing natural vegetation with deep-rooted pasture species. For example, in Latin America, *Brachiaria* grasses have been widely adopted; animal productivity can be increased by 5–10 times compared with animals subsisting on diets of native savanna vegetation. In Brazil, where about 99 million hectares have been planted, annual benefits are about US$4 billion. In the humid-subhumid livestock of systems of Latin America, the total mitigation potential of improved pastures such as *Brachiaria* is estimated to be 44 Mt. CO_2-eq (Thornton and Herrero 2010; Rao et al. 2014). However, while such practices will generally improve pasture quality and animal performance, they will not always reduce GHG emissions. For example, Henderson et al. (2015) found that while the inclusion of legumes in animal diets improved livestock productivity, the nitrogen emissions from sown legumes exceeded soil carbon sequestration benefits in most grasslands. Similarly, the addition of nitrogen fertilizer in a grazing system may reduce methane emissions but increase nitrous oxide emissions (FAO 2013). A third way in which grazing management may deliver productivity, mitigation and adaptation benefits is by balancing and adapting grazing pressure on land, though the effects are highly dependent on the context, such as plant species and soil and climatic conditions, for instance (Smith et al. 2008). Bozkurt and Kaya (2011) reported substantially improved grazing performance of beef cattle on upland rangeland conditions in Turkey from rotational grazing compared with set stocking, while Moyo et al. (2011) found no benefit in animal performance using rotational grazing schemes in the communal areas of Zimbabwe without controlling stocking rates in relation to the season's rainfall. In colder conditions in the Chinese steppe, Ma et al. (2014) found pronounced effects of grazing intensity and grazing period on sheep and grassland productivity, with deferred spring grazing combined with higher stocking rates in summer and relatively low stocking rates in autumn found to be a sustainable grazing strategy for these conditions. Any grazing management that enhances the quality and digestibility of the forage potentially improves livestock productivity and reduces the intensity of GHG emissions in the same way as for diet intensification.

There are considerable constraints associated with these grazing management options in the smallholder mixed systems of the tropics, however. First, managed pasture systems will require considerable investment costs (for fencing, watering points) and additional labour (FAO 2013). Second, such systems require high levels of technical capacity to operate and maintain. As noted above, the adoption rates of improved pastures in humid-subhumid Latin America have been high, but in smallholder mixed systems of SSA, adoption rates have been considerably lower for a range of reasons (see Sumberg (2002) in relation to fodder legumes). There may also be governance issues: replacing free grazing systems with cut-and-curry systems (as is happening in parts of Ethiopia, for example) may benefit pasture and animal productivity, but it requires changes in community bylaws and the development of mechanisms that can enforce the rules for zero grazing. For the arid and semi-arid systems in the tropics and subtropics, in general, there are far fewer opportunities for feasible grazing management options.

2.12 Alter Integration Within the System

Various options are available to smallholders in mixed systems involving changes to the proportion of crops to livestock and additions or subtractions to the enterprises that farmers engage in. Such changes can directly and indirectly affect the integration of the different elements in the farming system with respect to its resources of feed, manure, draft power and labour, and cash. Integrated crop-livestock systems offer some buffering capacity in relation to adaptation, with mitigation and resilience benefits too (Thornton and Herrero 2015). In many places smallholders are continually reassessing their activities, and risk reduction is often much more important than productivity increases per se (Kraaijvanger and Veldkamp 2015). In dry spells, farmers may reduce their investment in crops or even stop planting altogether and focus instead on livestock production (Thomas et al. 2007). Others may increase off-farm income in poor seasons via trading or some other business activity (Thornton et al. 2007). Remittances form an important source of income in some regions that can be invested in climate smarter activities (Deshingkar 2012). Such measures may help households to adapt and manage risk, though they may not necessarily deliver productivity and mitigation benefits directly, particularly in the short term (FAO 2013), though it could be argued that off-farm income invested in natural resource management-based alternatives may deliver such benefits in time. In the medium and longer term, smallholders may undertake more permanent (or semi-permanent) farming system transitions.

In marginal areas of southern Africa, reductions in length of growing period and increased rainfall variability are tending to push farmers to convert from mixed crop-livestock systems to rangeland-based systems, as farmers find growing crops too risky in marginal environments (Thornton and Herrero 2015). On the other hand, agricultural system transitions in some of the marginal areas of East Africa are operating the other way round: in recent years, the traditionally pastoral Pokot people of semi-arid north-western Kenya have started engaging in opportunistic cropping using residual moisture in dry river beds as a means of diversifying their livelihood options in the face of increasing rainfall variability and conflict over resources (Rufino et al. 2013). The addition of trees and shrubs to mixed farming systems can have well-documented benefits on animal production (Kaitho et al. 1998; Tuwei et al. 2003) as well as on mitigation, as outlined in Sect. 2.10 above.

Options that alter the integration of enterprises within mixed systems may deliver multiple benefits, although it is likely that there will be some tradeoffs that have to be made in the short term with respect to mitigation, productivity and food security (FAO 2013). There is still limited information currently that quantifies what these tradeoffs are in different contexts (e.g. Tschakert 2007), and given the prevalence of smallholder mixed systems in the tropics and subtropics, this warrants considerable attention (Thornton and Herrero 2015). At the same time, any change towards climate-smarter agriculture needs to have direct, short-term financial benefits for farmers, otherwise adoption is not likely to occur. In addition to potential short-term losses associated with these tradeoffs, there may be other obstacles to smallholder farmers making what may be quite radical changes to their farming and livelihood systems, related to cash availability and the technical know-how that new or unfamiliar crops or livestock species may require. There may be cultural constraints to their adoption as well. Lack of information, or of adequately packaged and communicated information, concerning likely seasonal weather conditions or longer-term climatic trends and economic conditions may also act as barriers to famers' being willing to make substantial changes to their production and livelihood systems (FAO 2013).

2.13 Water Use Efficiency and Management

Improving water use efficiency and water management on mixed farms is arguably the most important and high potential improvement for farmers to be climate-smart. An assessment of more than 60 economic studies of various management practices ranging from alley cropping to tillage and fertilizer indicates that water management strategies increase net returns and purchasing power parity of households much more than any other and perhaps presents the only viable pathway to help transition smallholder farmers out of poverty (Harris and Orr 2014). Without a doubt, the ability to supply water, mitigate the impacts of variable rainfall on crops, pasture and animals, and extend growing seasons has significant impacts on smallholder livelihoods, increasing yields and economic returns (Burney and Naylor 2012; Kurwakumire et al. 2014; Thierfelder and Wall 2009; Gebrehiwot et al. 2015). As an alternative to establishing irrigation schemes, more passive water harvesting techniques can equally yield big gains for smallholders. Small-scale water harvesting can include practices such as digging zai pits for individual plants and constructing ditches, terraces or stone lines to direct water to where it is needed. Simple techniques conserve soil moisture and improve productivity of most crops (Amede et al. 2011; Zougmoré et al. 2004). Water harvesting is often already a locally adapted measure and there are well known examples such as the Fanya-juu terraces for vegetable and staple production and chaco dams to increase water availability for cattle and other livestock in East Africa. Large-scale investments in soil and water conservation in northern Ethiopia, combined with collective action and conducive policy environments, has transformed semiarid, degraded lands into productive farming systems that are far less prone to droughts, thus transforming smallholder livelihoods and food security (Walraevens et al. 2015).

The promise of water management and increasing water use efficiency for improving livelihoods, especially under more variable weather conditions, has led to calls for this to be a priority investment (Burney et al. 2013; Rockström and Falkenmark 2015). Will water management transform smallholder mixed systems? Like other technologies, adoption of improved water management is significantly constrained by social, economic and environmental factors. In some cases, the labour hours required to dig channels and planting basins as such outweigh the perceived benefits or the labour is simply not available at the time of peak demand (Drechsel et al. 2005). This may often require community investment and collective action, and associated policy change and institutional mobilisation (Mengistu 2014). In addition to high labour demands, farmers in the highlands of Ethiopia are often reluctant to construct stone terraces in their fields due to the pest harbouring effects, as crop losses may outweigh yield gains (Teshome et al. 2014). These factors can reduce the attractiveness of water harvesting to producers. Furthermore, water management typically requires investments, capital for technologies such as pumps or boreholes or time for building terraces. In many cases, farmers are hesitant to make such investments without appropriate land rights (Lanckriet et al. 2015). Zimbabwe, for example, saw very low levels of adoption of key water saving technologies in the arid and semi-arid zones throughout the late twentieth century due to political instability and insecure tenure rules (Nyamadzawo et al. 2013). Thus, while the potential of water management for smallholder productivity is significant, so are the challenges; greater attention is needed to build the enabling environment for adoption than to develop new technologies.

2.14 Food Storage

The significance of food losses for smallholder farmers in Africa, including in mixed systems, is categorically different than in the developed world. Consumer waste, responsible for 95–115 kg food per person per year in developed countries (FAO 2011), is typically not a serious problem in developing countries or more specifically in crop-livestock systems. In contrast, food losses in SSA occur during the postharvest phases where due to a lack of information on harvesting techniques, storage facilities, and pests and diseases cause losses at a near equivalent amount (30–40%) to that of consumer waste in developed countries (Affognon et al. 2015). For example, postharvest losses of grains in Tanzania occur in the field (15%), during processing (13–20%), and during storage (15–25%) (Abass et al. 2014). Postharvest losses can be reduced using existing low-cost technologies and methods, many of which have been adopted rapidly in Asia, but are not widely used in SSA. Baoua et al. (2012) show that any number of techniques ranging from simple mixing of cowpea grain with ash to more advanced and costly storage in hermetically sealed plastic bags significantly reduce pest infestation, by more than 50%. Though the appropriate strategy to reduce losses needs to be tailored to the enterprise (resources available, market orientation, and commodity), an ample number of approaches are already available, even for small-scale producers, such as harvesting in the morning and separating out pest infected produce, and general principles to develop best practices are known for crops (Kitinoja and Kader 2003).

Storage of highly perishable animal products, milk and meat, as well as of higher-value vegetables and fruit, present unique challenges in resource limited and small-scale producer environments and have received markedly less attention. But gaps in knowledge should not discourage promotion of postharvest interventions, gains in food availability due to better storage practices at even modest levels of loss reduction (for example 10–15%) anywhere on the farm would have cascading impacts on food and nutrition security, adaptive capacity and the climate, though it is difficult to predict by precisely how much.

Many factors contribute to postharvest loss including mechanical injuries, water stress, physiological disorders, temperature, humidity, wind, marketing systems, regulations, a lack of tools, and equipment of information; many of these are recalcitrant problems obstructing agricultural development more generally. However, given that few other interventions offer the immediate ability to increase food availability by such a margin in such a short period, it is troubling how little effort is being directed toward solving this issue compared with increasing production, especially when the latter will become even less tenable under climate change.

2.15 Food Processing

Like improved postharvest storage methods, food processing presents an opportunity to extend the shelf-life of perishable farm products. Food processing, however, adds an additional layer of utility; it provides a mechanism for smallholders to add value to products at the farm gate. In mixed systems, farmers typically have potential to create fermented milk products, dried meat products as well as creating derivatives from crop products. By reducing the speed of food degradation, food processing increases or at least maintains the level of consumable farm output. Food processing also typically generates value-addition and/or an extra product that can be sold into the market, facilitating livelihood diversification by creating an alternative revenue stream. Improved longevity of production and increased marketability may make smallholders less susceptible to the annual cycles of food insecurity and less vulnerable to shifting weather patterns. Smallholder participation and integration into markets cannot be taken as a foregone conclusion, however. A link between food processing and GHG emissions can also be drawn. Similar to other postharvest methods that preserve food, increased food availability may decrease production-related emissions, assuming that demand and output remain constant. When processing requires energy and facilitates off-farm transport, it is important to consider the full lifecycle emissions of the product to understand the net climate impacts of production.

2.16 Use of Weather Information

Smallholders in rainfed mixed systems are vulnerable to weather variability both between seasons and within a season. They deal with this variability in several ways, usually building on long experience. The uncertainty associated with rainfall variability can be reduced through the use of weather information and climate advisories, enabling smallholders to better manage risks and take advantage of favourable climate conditions when they occur (Hansen et al. 2011). Reducing smallholders' vulnerability to current climate risk is often seen as one of the most appropriate entry points into future adaptation, given that climate change may most often be experienced as changes in the frequency and severity of extreme events. The provision of appropriate weather information and associated advisories can help smallholders make more informed decisions regarding the management of their crops and livestock, leading to increased productivity. The effective use of weather information may also be able to contribute to resilience by helping smallholders better manage the negative impacts of weather-related risks in poor seasons while taking greater advantage of better-than-average seasons. Use of weather information may also contribute to GHG emissions mitigation in some situations – for example, by better matching the use of fertilizer and other crop and pasture production inputs with prevailing weather conditions.

Climate services for agriculture are being scaled up in several developing countries. For example, some 560,000 rural households in Senegal now have access to climate information services via rural radio, provided by journalists trained to understand and communicate climate information in local languages and in an interactive format to engage listeners (Ndiaye et al. 2013). In this and other cases, demand for weather information is clearly driven by farmers. There is much less evidence as to how such weather information is being used, however, and the extent to which its use contributes to increased resilience and productivity (and any mitigation co-benefits). Robust impact assessment of the use of weather information and its effects on development outcomes (in addition to climate smartness) in developing country situations is sorely needed. There are several important constraints to the use of climate services, which include bridging the gap between the content, scale, format and lead-time that farmers need and the information that is routinely available (Hansen et al. 2011); ensuring that the information produced is credible, and that it can be understood and appropriately acted upon; and in ways that do not disadvantage economically and socially marginalized groups. One approach, based on combining climate information with participatory farm planning and budgeting tools, is showing promise in helping to overcome some of these constraints (Dorward et al. 2015) in pilot studies in Tanzania and elsewhere.

2.17 Weather-Index Insurance

Agricultural insurance is one approach to managing weather-related risks; it normally relies on direct measurement of the loss or damage suffered by each farmer, which can be costly and time consuming. An alternative is index-based insurance that uses a weather index (e.g., amount of rainfall in a specified period) to determine payouts for the hazard insured. Index-based insurance for crops is often based on rainfall received at a particular meteorological station, with thresholds set for making lump-sum or incremental payouts to those insured. In remote areas, another approach is to use an index based on satellite imagery of vegetation ground cover as a proxy for fodder availability to insure livestock keepers against drought (Chantarat et al. 2013). Index insurance is often coupled with access to credit, allowing farmers to invest in improved practices that can increase productivity and food security, even in adverse weather conditions. In many parts of the global tropics, rainfall is highly variable, and many smallholders inevitably experience livestock loss and crop yield reductions if not total crop failure. Index insurance can make a substantial contribution to smallholders' resilience.

Agricultural insurance is being applied in a range of situations in the developing world. In India, for example, national index insurance programmes, linked to agricultural credit provision and enabled with strong government support, have reached more than 30 million farmers. The Agriculture and Climate Risk Enterprise (ACRE) program in East Africa now reaches nearly 200,000 farmers with bundled index insurance, agricultural credit and farm inputs (Greatrex et al. 2015). Index insurance may have few direct mitigation co-benefits, but smallholders may be able to enhance carbon sequestration or reduce GHG emissions via the management decisions they make as a result of being insured.

Since the 1990s, there has been considerable debate about the potential uses of index-based insurance to manage weather risks in agriculture. In addition to the challenge of basis risk, questions have been raised as to its general scalability (Hazell et al. 2010). There is also a substantial challenge in reconciling simplicity, transparency and efficiency in weather-index insurance programs: they are often complicated instruments needing outreach, education and extension, and the building of trust through time. A key challenge is that the current evidence base as to the impacts of weather-index insurance is weak; when applied at scale in different contexts, the tangible and sustainable impacts on poverty and food security are not yet clear. Nor is it clear whether changes in farmers' production practices tend to increase or decrease farm-level income risk. There may be equity issues too: provision of weather-index insurance to some may exacerbate the losses of segments of society that cannot purchase insurance (Miranda and Farrin 2012). As for climate services, robust impact assessments of weather-index insurance and its relative climate smartness are greatly needed.

3 Adoption Constraints and the Potential for Uptake of CSA Interventions

As shown in the previous section, a wide range of options exists for mixed crop-livestock farmers in developing countries, and many of these have positive impacts on at least one or two of the three CSA pillars, and some on all three. The evidence base is mixed, however: the scientific literature for some of these options is scanty, and the survey results of expert opinion clearly show that local context can have an over-riding influence on whether particular practices are positive or negative in any particular situation, given that some 40% of the impacts shown in Table 2 are adjudged to be uncertain. One key message from this analysis is that broad-brush targeting of CSA interventions is apparently not appropriate, from a technical standpoint, given that the impacts are often not clear and/or highly context-specific. The technical potential of CSA interventions in developing country agriculture is going to remain difficult to estimate for some time to come.

Independent of context, common elements can be identified that are important to facilitate the adoption of CSA in developing countries, while these tend to be similar to those that characterise the adoption of other types of sustainable agricultural development or natural resource management strategies. In light of the limited capacity of smallholders to bear risk, they tend to select farm portfolios that stabilise income flows and consumption (Barrett et al. 2001). Under climate change, this ability is determined by high-level factors such as the need for conducive enabling policy environments and public investment, the assurance of peace and security, stable macro-economic conditions, functioning markets and appropriate incentives (or the development of these, including financial, labour, land and input markets), as well as the ability and willingness of farmers to invest their own human, social, natural and physical capitals (Westermann et al. 2015; Ehui and Pender 2005). Socio-cultural traditions, including structural social inequalities, marginalisation of specific groups and gender relations, local institutions (that include informal rules and regulations) that guide resource use, and the division of labour and household decision making, all play a key role in determining whether climate smarter practices are feasible in specific locations.

With respect to agricultural technology adoption and uptake in general, many of the CSA interventions discussed in Sect. 2 have different constraints. These are laid out in Table 2 by intervention, for the following constraints:

- Investment cost: the upfront infrastructural and/or technological costs that farmers may have to make before some types of intervention can be implemented, such as fencing material or irrigation equipment.
- Input/operating cost: these are the recurring costs of inputs needed, including labour, fertilizer or hybrid seed.
- Risk: certain technologies in some situations (e.g., higher levels of purchased inputs in places with high rainfall variability) may have unintended impacts on production or income variability, which can severely constraint adoption.

Table 2 Constraints to the widespread adoption of climate-smart options (Table 1 and Sect. 3) available to smallholders in mixed crop-livestock systems in developing countries

	Constraint									
Option	Investment Cost	Input/operating cost	Risk	Access to technology	Technical know-how	Temporal trade-offs	CSA trade-offs	Information	Acceptability	State of evidence base
2.1 Change crop varieties		*		**				*		
2.2 Change crops		*	*	*	*			*	*	
2.3 Crop residue management		*	*			**	*		**	
2.4 Crop management		*	*					**	*	
2.5 Nutrient management		**			*	*	*			
2.6 Soil management	*	*			*	*	*			
2.7 Change livestock breed	**	*	*	*	**	*		*	**	*
2.8 Manure management	*(*)			*	**		*	**	*	**
2.9 Change livestock species	**	*	*	*	**	*		**	**	*
2.10 Improved feeding	*	**		*	*		*	*	*	
2.11 Grazing management	**	*		*	**	*	*	**	*	

2.12 Alter system integration	*		**		*	**	*	**	**	**
2.13 Water use efficiency / mgmt	**	**		*	*	*	*		**	
2.14 Food storage					*			*	*	**
2.15 Food processing	*	*			*		?		*	**
2.16 Use of weather information				*	*	*	*?	*	*	**
2.17 Weather-index insurance	*		*	**	**	*	*?	**	*	**

Importance of constraint: **major, *moderate,? unknown and/or highly context-specific. Authors' evaluation

- Access to technology: adoption may well be constrained in situations where smallholders have limited physical access to the technology (e.g. seeds of improved varieties of crops or pastures).
- Technical know-how: some interventions require high levels of technical knowledge about how to implement and manage the option, and this may act as a powerful deterrent to adoption.
- Temporal trade-offs: sometimes trade-offs may need to be made in the short term to realise medium- or longer-term benefits (e.g., losing access to a piece of land while waiting for certain cash crops to produce harvestable yield), and farmers may not have the wherewithal to wait for these benefits to materialise.
- CSA trade-offs: some interventions in some situations may involve trade-offs between the CSA pillars (production, resilience and mitigation objectives); productivity-enhancing technology may increase resilience by improving household cash flow, but may increase GHG emissions or emission intensities at the same time (e.g., adding nitrogen fertilizer under some circumstances).
- Information: some interventions have recurring informational needs such as seasonal weather forecasts.
- Acceptability: some CSA interventions may go against socio-cultural norms, directly affecting a technology's acceptability in a community (e.g., practices that may affect communal grazing governance in a location, or weak land tenure arrangements affecting the acceptability of investment).
- State of evidence base: insufficient evidence to be able to make robust statements about the relative climate smartness of different alternatives in differing contexts may indirectly constrain their uptake.

Table 2 demonstrates clearly that all interventions are associated with some constraints that may affect adoption in different circumstances. Despite the constraints, all of these interventions may be suitable in some circumstances, but identifying those circumstances may not be straightforward. This is a serious knowledge gap. The scale of the agricultural production and food security challenge in the coming decades is known well enough: by 2030, population may be 8.5 billion, with still-rapid growth in SSA in particular (UNPD 2015). Much of the food production needed will be produced by smallholder mixed farmers, whose numbers are projected to increase from about 560 million today to some 750 million by 2030, mostly in SSA and Asia (Campbell and Thornton 2014). Many of these current and future smallholders will have to become adopters of climate-smart interventions if future food demand is to be satisfied in sustainable ways. Currently, there is only limited information concerning the potential uptake of CSA interventions at scale, in terms of geographic or other domains. A highly indicative analysis is shown in Box 1 for SSA, as a simple example; much more robust and detailed information than is contained in Box 1 would be of considerable value in helping to target research-for-development initiatives to overcome the key adoption barriers in particular places and to prioritise investments in CSA.

Box 1 Towards prioritising investments in CSA: sub-Saharan Africa as an example

One preliminary step towards generating the information needed to prioritise investments in CSA is identifying those locations where different interventions may be profitable for smallholders, feasible given their biophysical, informational and socio-economic constraints, and socio-culturally acceptable. As an illustration, we mapped the 17 interventions outlined in Sect. 2 to spatial domains in sub-Saharan Africa based on the mixed system classification shown in Table 1. We used the potential impacts of the intervention from Table 1 and the nature of the constraints to adoption from Table 2, and then subjectively evaluated the suitability of each intervention as zero, low, medium or high in each system. One way to evaluated suitability is in relation to potential adoption rates. To date, adoption rates of agricultural technology in SSA have not often exceeded 30% over one or two decades (see, for example, a discussion in Thornton and Herrero (2010)). Accordingly, we used potential adoption rates of 5% (low suitability) 15% (medium suitability) and 30% (high suitability), nominally for the period to 2030, for the 17 CSA interventions in Table 1. For each intervention, we calculated the size of the rural area and the current number of rural people in each system, crudely multiplied by the associated adoption rate, and summed these to give a highly approximate indication of the relative size of the "suitability domain" (in terms of size and rural population) for each intervention. Results are shown in the table below. Improved feeding and altering the enterprise balance may be suitable over relatively large areas and for large numbers of people living in the rural areas, not all of whom are engaged in agriculture, of course (Lowder et al. 2014). Food storage, grazing management and changes in livestock species (particularly large to small ruminants, or ruminants to non-ruminants, for example) are also options with relatively large domains, according to this analysis. The results for food storage are noteworthy; this intervention appears to have solid CSA benefits (particularly related to increased food availability), and considerable effort and resources might well be warranted to increase the uptake of simple food storage technology and the availability of appropriate information.

There are many problems with this particular analysis: to name just three, the subjective nature of the suitability index, the fact that potential adoption rates are likely to be context- and intervention-specific, and the lack of specificity as to what the exact intervention actually is in each category (for instance, "improved feeding" is a broad term covering many different types of intervention). Nevertheless, this type of broad-brush analysis, if done on a global basis in relation to specific interventions and with as much quantifiable information as possible, could be very helpful in prioritising investments in CSA over the next few years (Table B1).

4 Conclusions

The analysis presented here is largely qualitative, based on a systematic review protocol coupled with a survey of experts. We recognise this as a weakness, but as noted in Sect. 1, at present we lack comprehensive information on the costs, benefits, synergies and trade-offs of many of the interventions examined. This is partly because the current state of science for CSA in the mixed systems in developing countries is sparse. There are gaps in our understanding of some of the key biophysical and socioeconomic interactions at the farm level, and work remains to be done before we can inform agricultural development planning for food security in the face of climate change, particularly at the household level, with the accuracy scientists typically strive for.

At the same time, we do not lack analytical tools and methods that could be used for quantitative priority setting to help allocate the resources needed to stimulate the widespread adoption of CSA. To overcome the dearth of field-based evidence on CSA practices and their interactions, modelling tools for the *ex ante* evaluation of these practices will be particularly useful in these early stages of CSA programming. Process-based models such as APSIM (Keating et al. 2003) and IAT (Lisson et al. 2010) can further our understanding of key biophysical interactions under a range CSA management options in the absence of empirical field results (Rigolot et al. 2016). The outputs of these models can in turn be used to help specify the biophysical relationships in bio-economic models suited to the *ex ante* assessment of CSA practices. Mathematical programming techniques can be used to construct bio-economic models that are well-equipped to evaluate CSA practices and help rank practices based on their economic viability in the presence of risk. Their strength lies in their flexibility to incorporate multiple interactions, such as those characterised by CSA, as well as flexibility to include a variety of constraints (Hazell and Norton 1986), including many of those identified in Table 2. Their weakness is in their generally normative nature, as farmers do not tend to behave as optimally as these tools suggest, due in part to various non-economic and non-biophysical considerations that affect farmer decision making. However, recent developments in the growing field of positive mathematical programming have considerably improved the reliability of these models to more accurately simulate farmer behaviour (Mérel and Howitt 2014; Qureshi et al. 2013). Given that the success of CSA practices is highly context-dependent, the usefulness of *ex ante* analyses will have to explicitly account for the heterogeneity of farms and adoption impacts within rural populations and landscapes. This will in turn depend on adequate representation of farm populations in household survey data coupled with spatial data on farming systems, especially when assessing the potential for adoption at regional scales. Naturally, there is no substitute for field-based research and *ex post* analyses of the adoption CSA practices and their economic impacts. As more field and survey-based data accrue over time, these *ex post* analyses can run in parallel with and complement *ex ante* analyses, further building the evidence base for CSA practices and policies.

Table B1 Agricultural system domains where climate-smart options (Table 1 and Sect. 2) for smallholders in mixed crop-livestock systems in sub-Saharan Africa may be suitable. Relative suitability: 0, not suitable; 1 (low), 5% potential adoption; 2 (medium) 15% potential adoption; 3 (high), 30% potential adoption. EM, extensive mixed systems; IM, intensifying mixed systems (From Herrero et al. 2009; see Fig. 1). Population data from CIESIN (2005). Suitability ratings are the authors' own estimates.

	"Suitability"		Total area (km^2 million)	Total rural population (million 2000)
Option	EM	IM		
2.1 Change crop varieties	1	3	0.67	60.62
2.2 Change crops	2	3	1.12	85.78
2.3 Crop residue management	0	1	0.07	8.01
2.4 Crop management	1	2	0.45	36.60
2.5 Nutrient management	1	2	0.45	36.60
2.6 Soil management	1	2	0.45	36.60
2.7 Change livestock breed	2	3	1.12	85.78
2.8 Manure management	2	2	0.91	61.76
2.9 Change livestock species	3	2	1.59	99.50
2.10 Improved feeding	3	3	1.81	123.52
2.11 Grazing management	3	2	1.59	99.50
2.12 Alter integration between crops and livestock	3	3	1.81	123.52
2.13 Water use efficiency	2	1	0.76	45.75
2.14 Food storage	3	2	1.59	99.50
2.15 Food processing	1	2	0.45	36.60
2.16 Weather information	3	1	1.45	83.49
2.17 Weather-index insurance	2	2	0.91	61.76

Despite the limitations of the analysis conducted here, some conclusions can be drawn. First, from a technical perspective, there appear to exist no "silver bullets" for achieving climate-smart mixed systems. While this echoes the conclusions of the semi-quantitative analysis in Thornton and Herrero (2014), here we looked at a much wider range of possible interventions than was done there. Triple wins undoubtedly exist, but technical recommendations over broad domains that will work in all or even most circumstances may not be appropriate. Second, from an adoption perspective, a range of different constraints exist that may impede the widespread adoption of all these innovations. These may be to do with investment and/or running costs and access to technology and knowledge of how to implement it, as well as social acceptability and local governance issues. In different contexts, these may conspire to prevent the incremental and transformational shifts that may be needed to result in more climate smart agriculture in many places. Third, for some of the interventions evaluated, there are significant trade-offs between meeting shorter-term food production or food security objectives and longer-term resilience objectives. This applies particularly to crop residue management and altering the integration of crops and livestock within the system, but also to several other interventions (nutrient, soil, water management; grazing management; changing livestock species and breeds; and use of weather information and weather-index insurance). These temporal trade-offs may be difficult to resolve in many local contexts, and the triple wins involving these interventions will sometimes be elusive.

Despite some key knowledge gaps, the lack of silver bullets, the constraints to adoption, and the trade-offs that may arise between shorter- and longer-term objectives at the household level, much is being done. As noted above, more comprehensive information could help target interventions more effectively and precisely, but in many situations, there is already appropriate information to enable no-regret interventions to be suggested – those that already fit in well within current farming practices and do not significantly increase labour demands and household risk, for example. Impacts of adoption of CSA interventions are already appearing (e.g., Nyasimi et al. 2014) and countries such as Myanmar and Cambodia are developing national agricultural strategies around CSA (Hom et al. 2015; CCAFS 2016).

Evidence is also accumulating of the kinds of approaches that can support the scaling up of CSA interventions. Multi-stakeholder platforms and policy making networks are key, especially if paired with capacity enhancement, learning, and innovative approaches to support decision making of farmers (Westermann et al. 2015). Modern information and communications technology offers efficient and cost-effective ways to disseminate and collect information at massive scale, as well as an infrastructure for developing and utilising new and diverse partnerships (with the private sector, for example). A certain level of local engagement may still usually be needed, paying attention to farmers' needs and their own situations (Westermann et al. 2015).

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