CHAPTER 4

Climate-Smart Agriculture Options in Mixed Crop-Livestock Systems in Africa South of the Sahara

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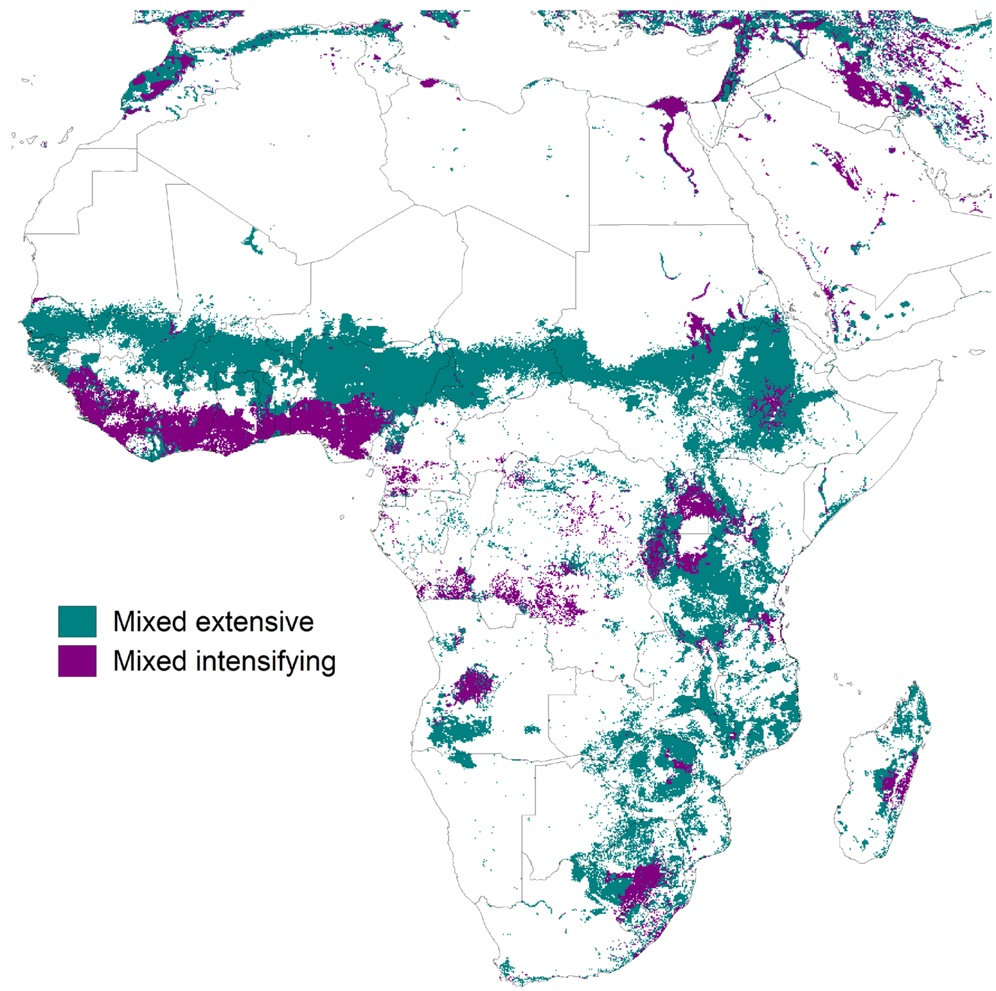
Mixed crop-livestock systems, in which crops and livestock are raised on the same farm, are the backbone of smallholder production in most of Africa south of the Sahara. They have considerable potential for increasing agricultural production for food security, helping farmers adapt to a changing climate, and providing mitigation benefits: these benefits constitute the three pillars of climate-smart agriculture (CSA). The synergies and trade-offs among these three pillars are not well studied or understood; there is very little robust information in the published literature that evaluates all three pillars of CSA practices. This chapter presents a qualitative analysis that prioritizes investments in CSA in Africa south of the Sahara on a broad scale and concludes with a brief discussion of some of the associated technical and policy implications of current knowledge as well as key knowledge gaps.

Mixed crop-livestock systems are central to smallholder production in the developing countries of the tropics (Herrero et al. 2010). Globally, they produce 69 percent of the world's milk and 61 percent of the meat from ruminants; in Africa south of the Sahara (SSA), they produce more than 90 percent of the milk and 80 percent of the meat from ruminants (Herrero et al. 2013). Figure 4.1 shows the location of mixed systems in Africa, defined as those in which more than 10 percent of the dry matter fed to animals comes from crop by-products or stubble, or more than 10 percent of the total value of production comes from non-livestock farming activities (Seré and Steinfeld 1996). This map distinguishes two types of mixed systems: "extensive," with lower agroecological potential (an annual length of growing period [LGP] of fewer than 180 days per year) and "intensifying," with higher agroecological potential (having an LGP of 180 or more days per year) coupled with better access to urban markets (less than 8 hours' travel

FIGURE 4.1—MIXED CROP-LIVESTOCK SYSTEMS IN AFRICA



Source: Herrero et al. (2009), using a mapped version of the livestock classification system of Seré and Steinfeld (1996).

time to an urban center with a population of more than 50,000). The great majority of these mixed systems are rainfed.

In mixed 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. Appropriate integration of crop and livestock activities can lead to greater farm efficiency, productivity, and sustainability (Sumberg 2003), as well as increasing farmers' incomes (Descheemaeker, Amede, and Haileslassie 2010). Mixed systems offer key livelihood diversification options to smallholders in developing countries who aim to minimize the risk associated with agricultural production, liquidity constraints, and high transaction costs, all of which can result in income and consumption fluctuations (Dercon 1996; Davies et al. 2009; Barrett, Reardon, and Webb 2001). These diversification options offer alternatives for addressing some of the challenges posed by a changing climate and increasing climate variability in the future (Thornton and Herrero 2015). The mixed systems also have a role to play in mitigating greenhouse gas (GHG) emissions from the agriculture, forestry, and land-use sectors. Although livestock systems are a considerable source of GHG emissions, the emissions intensities of mixed systems are 24–37 percent lower than those of grazing systems in Africa (Herrero et al. 2013), mostly because of higher-quality ruminant diets. Other mitigation opportunities are afforded by manure amendments for crop production and carbon sequestration in soils and biomass (Liu et al. 2010; Seebauer 2014).

Mixed farming systems have various characteristics that may be advantageous in some situations and disadvantageous in others (van Keulen and Schiere 2004). For example, when conditions are appropriate, the use of draft power allows larger areas of land to be cultivated and planting to be completed more rapidly. On the other hand, these advantages may mean that extra labor (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 to livestock may compete with other uses of this material, such as mulching, construction, and nutrient cycling. A major constraint to increased crop-livestock integration is that these systems can be complex to operate and manage (van Keulen and Schiere 2004; Russelle, Entz, and Franzluebbers 2007). Nonetheless, integration may offer one pathway whereby smallholders can increase their livelihood security while reducing their vulnerability to food insecurity as well as to climate change (Thornton and Herrero 2015).

Comprehensive evaluations of the costs and benefits, and the synergies and trade-offs, of different options in African mixed systems are underway, drawn from extensive searches of published literature (Rosenstock et al. 2015, 2016). To date, very few studies have included quantitative evaluation of all three components, or pillars, of climate-smart agriculture (CSA): increasing agricultural production for food security, helping farmers adapt to a changing climate, and providing mitigation benefits. Generalization is thus difficult, and local context has a considerable effect on whether trade-offs or synergies will arise when CSA options are implemented (Rosenstock et al. 2015). This chapter outlines crop and livestock management interventions that may be able to deliver multiple benefits (food security as well as improved climate change mitigation and adaptation) in different situations in SSA. To evaluate how these farm-level CSA management practices and technologies may affect food production, adaptive capacity, and climate change mitigation, we use the protocol of Rosenstock and colleagues (2016), supplemented by a survey of experts, to determine whether the practice has a positive, negative, or undetermined impact on productivity (production per hectare or per animal), resilience (via variables that help buffer the system against shocks and stresses, such as soil organic carbon and input use efficiency, for example), and mitigation (via emission reductions or avoidance). The next sections provide brief descriptions and evaluations of CSA interventions, and discuss constraints to the uptake of these interventions and the potential for their adoption at scale. A simple spatial analysis of potential domains of adoption of these interventions is then presented. The chapter concludes with 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 SSA.

Climate-Smart Agriculture Interventions in Mixed Systems

Climate-smart options for mixed crop-livestock systems vary widely in their potential impacts on agricultural productivity, climate change resilience, and GHG mitigation. Table 4.1 shows results of an expert survey on 17 CSA options delineated by the Food and Agriculture Organization of the United Nations (FAO 2013). Although most options will improve productivity, impacts on resilience and mitigation are particularly variable due to context specificity. The nine experts surveyed felt that it was particularly difficult to generalize about mitigation impacts, in view of the importance of the precise context and the local situation, and this feeling is reflected in the number of options in Table 4.1 for which the mitigation impacts are judged to be uncertain. It should be stressed again that for some of the interventions, the strength of evidence to support the assessments is quite limited, hence the reliance on expert opinion. The 17 options are very briefly described below.

TABLE 4.1—CLIMATE-SMART OPTIONS AVAILABLE TO SMALLHOLDERS IN MIXED CROP-LIVESTOCK SYSTEMS IN DEVELOPING COUNTRIES: POTENTIAL IMPACTS AND STRENGTH OF EVIDENCE

Region	Potential impacts			
	Production	Resilience	Mitigation	Strength of evidence
Changing crop varieties	+	+/-	+/-	***
Changing crops	+	+	+/-	*
Crop residue management	+/-	+	-	**
Crop management	+	+/-	+/-	*
Nutrient management	+	+	+	***
Soil management	+	+	+/-	**
Changing livestock breed	+	+	+	*
Manure management	+	+/-	+/-	*
Changing livestock species	+	+/-	+/-	*
Improved feeding	+	+/-	+/-	**
Grazing management	+	+	+/-	**
Altering integration within the system	+	+	+	*
Water use efficiency and management	+	+	+/-	**
Food storage	+	+	+	*
Food processing	+	+/-	+/-	*
Use of weather information	+	+	+/-	-
Weather-index insurance	+	+/-	+/-	*

Source: Scoring based on authors' assessment of the articles found in a systematic review of climate-smart agriculture literature (described in Rosenstock et al. 2016), supplemented with an informal survey of nine experts. CSA options from FAO (2013).

Note: The results of the survey were averaged to determine the impact of the practice on the key climate-smart agriculture indicators. Potential impacts: + = positive; - = negative; +/- = uncertain. Strength of evidence: *** = confident; ** = likely; * = poor, - = speculation.

Changing crop varieties: Adaptation strategies such as improved varieties may reduce projected yield losses under climate change, particularly for rice and wheat in the tropics (Challinor et al. 2014). High-yielding varieties can improve the food self-sufficiency of smallholders and increase their income without the need to cultivate extra land. Drought-tolerant varieties have helped to stabilize yields, particularly of cereal crops in rainfed systems (La Rovere et al. 2014). As droughts, pest and disease outbreaks, and water salinization become more common with climate change and increasing demands on natural resources, shifts in crop varieties will continue to be among the first lines of defense 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, many different crops, including feed and forage species as well as trees or fodder shrubs, contribute to the resilience of the system, but their climate resilience and contribution to smallholder well-being are not always well understood.

Changing crops: Climate change will modify the areas suitable for cultivation of staple crops, requiring farmers to switch crops in some places (Vermeulen et al. 2013). Maize, beans, bananas, and finger millet, staple crops in much of SSA, could experience a reduction of 30–50 percent in areas suitable for cropping (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 may increase resilience to climate change. Though 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 nonexistent. 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 capitalize by planting crops appropriate to the changing climatic conditions.

Crop residue management: Crop residue management practices determine the destination and use of stover and other crop by-products. Some effective residue management solutions retain plant residues and use 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 by protecting the soil surface from rainfall (Lal 1997). Cover cropping typically includes the growing of a nonharvested or partially harvested crop, either in a crop rotation or outside the main growing season. Cover cropping with leguminous crops can be very beneficial to the typically low-fertility and highly weathered soils common in smallholder systems (Snapp et al. 2005). Mulching can increase soil aggregation (Mulumba and Lal 2008) and thus enhance its physical quality, as well as protect soils from direct impact by rainfall, greatly reducing the loss of nutrients and organic matter through soil erosion (Barton et al. 2004).

Crop management: As local weather patterns become more unpredictable with climate change, farmers may need to adjust planting seasons accordingly. Changes in planting dates can have profound impacts on farm productivity (Shumba, Waddington, and Rukuni 1992). However, for some farmers, effective earlier planting may require adjusting cultivation practices in ways such as using pesticides and minimal 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 nonleguminous crops and trees (agroforestry). Intercropping can reduce risk substantially: crops in intercropping systems typically access different soil water and nutrient resources, have different water requirements, and have varying growth and maturity rates, all of which can reduce the risk of total crop failure (and the associated risk of food insecurity) due to erratic or decreased precipitation (Ghosh et al. 2006).

Nutrient management: Smallholders on mixed crop-livestock farms can control the distribution of nutrients by applying inorganic and organic fertilizers and composts, growing trees, recycling waste, and improving animal diets. These all have benefits for improving productivity, boosting water and nutrient use efficiency, and reducing the GHG intensity of production (Kimaro et al. 2015; Bryan et al. 2013; Zingore et al. 2007). The transfer of nutrient-rich materials (manure, residues, and feeds) between production activities may have cascading effects across the farm due to changes in available nutrients (van Wijk et al. 2009). For example, conservation agriculture may help to maintain soil chemical and physical properties, but crop residues in mixed systems are often fed to livestock, serving as a vital feed resource during periods of low supply (Giller et al. 2015). Conserving crop residues for soil fertility purposes may reduce the nutrients available to other subcomponents of the system, such as livestock.

Soil management: Managing the soil for climate-related risks often involves increasing its physical quality while maintaining or improving its fertility. Increased soil organic carbon and soil aggregation can lead to increased water infiltration and water storage for plant use. Climate change may negatively affect soil fertility and the mineral nutrition of crops (St. Clair and Lynch 2010). These aspects of soil quality can be addressed through the effective use of crop rotation and leguminous plants and via livestock density management. Crop rotation with leguminous plants may decrease disease incidence, suppress weed infestation, and enhance nutrient cycling (Mureithi, Gachene, and Ojiem 2003). Leguminous plants and trees can be effectively incorporated into smallholder systems through intercropping, relay cropping, and planting boundaries, with their nitrogen-fixing capabilities increasing soil fertility (Kerr et al. 2007).

Changing livestock breed: Local animal breeds 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 or meat) can be high. The utilization of more productive animals can provide not only higher productivity but also reduced emissions intensity. Livestock populations exhibit natural genetic variation, and selection within breeds of farm livestock may produce genetic changes in trait(s) of interest in the range of 1–3 percent per year (Smith 1984). Within-breed selection poses challenges because appropriate infrastructure such as performance recording and genetic evaluation programs may be lacking. Cross-breeding is usually more feasible. Locally adapted breeds can be utilized 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 (Thornton and Herrero 2010; Galukande et al. 2013).

Manure management: The utilization of livestock manure to add nutrients back to the soil is a key crop-livestock interaction in mixed farming systems. When used as a soil amendment, manure 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. Manure has well-documented impacts on soil chemical and physical properties (Srinivasarao et al. 2012; Taddesse et al.

2003). 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 they may exist in zero-grazing smallholder dairy systems, for example (FAO 2013).

Changing livestock species: The substitution of one species of livestock for another is one strategy that can be used to increase resilience to climatic and economic shocks: 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. In parts of the Sahel, dromedaries have replaced cattle, and goats have replaced sheep in the wake of the droughts of the 1980s (Hoffman 2010). In other areas, 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 with small animals than with larger ones. 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.

Improved feeding: Interventions that target improved feed resources can result in faster animal growth, higher milk production, earlier first calving, and increased incomes. Better nutrition can also increase the fertility rates and reduce the 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, 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). Such supplements can substantially increase productivity per animal while also increasing resilience by boosting income (Thornton and Herrero 2010) and reducing the amount of methane produced by the animal per kilogram of meat or milk produced (Bryan et al. 2013).

Grazing management: Native grasses in rangelands and mixed systems are often of relatively low digestibility. Pasture productivity can be increased through adding nitrogen and phosphorus fertilizers, adjusting the frequency and severity of grazing, changing plant composition, and utilizing irrigation. Particularly in the humid and subhumid 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, where Brachiaria grasses have been widely adopted, animal productivity can be increased by 5–10 times compared with diets of native savannah vegetation (Rao et al. 2014). Such options will not always reduce GHG emissions, however (Henderson et al. 2015). Another way in which grazing management may deliver productivity, adaptation, and mitigation 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 (Smith et al. 2008).

Altering integration within the system: Smallholders in mixed systems have various options involving changes to the proportion of crops to livestock, and additions or subtractions to the enterprises in which farmers are engaged. Such changes can directly and indirectly affect the integration of the different elements in the farming system with respect to feed, manure, draft power and labor, and cash. Integrated crop-livestock systems offer some buffering capacity for adaptation, with mitigation and resilience benefits too (Thornton and Herrero 2015). In many places, risk reduction may be 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; Deshingkar 2012). Depending on the context, these kinds of transitions may be permanent or semipermanent (Thornton and Herrero 2015; Rufino et al. 2013).

Water use efficiency and management: Improving water use efficiency and water management on mixed farms can have substantial benefits (Harris and Orr 2014). The ability to supply water; mitigate the impacts of variable rainfall on crops, pasture, and animals; and extend growing seasons can all have significant impacts on smallholder livelihoods, increasing yields and economic returns (Burney and Naylor 2012; Kurwakumire et al. 2014; Thierfelder and Wall 2009; Gebrehiwot, Mesfin, and Nyssen 2015). 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, thus conserving soil moisture and improving productivity (Amede, Menza, and Awlachew 2011; Zougmoré, Mando, and Stroosnijder 2004). Investments in soil and water conservation in northern Ethiopia, combined with collective action and a conducive policy environment, have transformed semiarid, degraded lands into productive farming systems that are far less prone to droughts than before, thus transforming smallholder livelihoods and food security (Walraevens et al. 2015).

Food storage: Food losses in SSA generally occur during and after harvest; harvesting techniques, inadequate storage facilities, and pests and diseases cause losses of 30–40 percent, a figure similar to the amount of consumer waste in developed countries (Affognon et al. 2015). Postharvest losses can be reduced by using existing low-cost technologies and methods, many of which have been adopted rapidly in Asia but are not widely used in SSA. Though the appropriate strategy to reduce losses needs to be tailored to the specific agricultural enterprise (in terms of resources available, market orientation, and commodity), several approaches are already available for cereal grains, even for small-scale producers (Kitinoja and Kader 2003). Storage of highly perishable animal products—milk and meat—as well as of higher-value vegetables and fruits presents unique challenges in resource-limited and small-scale producer environments, yet it has received markedly less attention than that of cereals.

Food processing: Like improved postharvest storage methods, food processing presents an opportunity to extend the shelf life of perishable farm products. Food processing also provides a mechanism for smallholders to add value to products at the farmgate. In mixed systems, farmers typically have the potential to create fermented milk and dried meat products as well as 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 or an extra product that can be sold on the market, facilitating livelihood diversification by creating an alternative revenue stream. Improved longevity and increased marketability of farm production may make smallholders less susceptible to the annual cycles of food insecurity and less vulnerable to shifting weather patterns. The impacts on GHG emissions may depend on context: increased food availability may decrease production-related emissions, but processing may require energy and off-farm transportation.

Use of weather information: Smallholders in rainfed mixed systems deal with rainfall variability in several ways, usually building on long experience. Uncertainty can be reduced through the use of weather information and climate advisories, enabling smallholders to better manage risks and take advantage of favorable climate conditions when they occur (Hansen et al. 2011). 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 mitigation in some situations—for example, by better matching the use of fertilizer and other crop and pasture production inputs with prevailing weather conditions.

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 (for example, the amount of rainfall in a specified period) to determine payouts for the targeted hazard. In remote areas, the index may be 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 bundled with access to credit and farm inputs, allowing farmers to invest in improved practices that can increase their productivity and food security, even in adverse weather conditions, thereby increasing their resilience (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.

Adoption Constraints and the Potential for Uptake of Climate-Smart Agriculture Interventions

As outlined above, a wide range of options exists for mixed crop-livestock farmers in developing countries, and many of them have positive impacts on at least one or two of the three CSA pillars, some on all three. The evidence base is mixed, however: the scientific literature for some of these options is very scanty, and the results of the expert opinion survey presented here clearly show that local context can have an overriding influence on whether particular practices have positive or negative effects in a certain situation, given that some 40 percent of the impacts shown in Table 4.1 are adjudged to be uncertain. One key message from this analysis is that broad-brush targeting of CSA interventions is not appropriate, from a technical standpoint, given that the impacts are often not clear or are highly context specific.

Independent of context, we can identify common elements that are important to facilitate the adoption of CSA in developing countries. These elements tend to be similar to those that characterize the adoption of other types of sustainable agricultural development or natural resource management strategies. In light of their limited capacity to bear risk, many smallholders tend to select farm portfolios that stabilize income flows and consumption (Barrett, Reardon, and Webb 2001). Under climate change, smallholders' ability to select such portfolios is determined by high-level factors such as conducive enabling policy environments and public investment; the assurance of peace and security; stable macroeconomic conditions; functioning markets and appropriate incentives (or the development of these, including financial, labor, land, and input markets); and the ability and willingness of farmers to invest their own human, social, natural, and physical capital (Ehui and Pender 2005; Westermann, Thornton, and Förch 2015). Sociocultural traditions, including structural social inequalities, marginalization of specific groups, and gender relations, as well as local institutions (with informal rules and regulations) that guide resource use, the division of labor, and household decision making also play a key role in determining whether climate-smarter practices are feasible in specific locations.

As for agricultural technology adoption and uptake in general, many of the CSA interventions outlined above have different constraints. These are laid out in Table 4.2 by intervention, for the following constraints:

- **Investment cost:** Farmers may face up-front infrastructural or technological costs before some types of interventions can be implemented, such as costs for fencing material or irrigation equipment.
- **Input and operating cost:** These are the recurring costs of the needed inputs, including labor, fertilizer, and hybrid seed.
- **Risk:** Certain technologies in some situations (for instance, higher levels of purchased inputs in places with high rainfall variability) may have unintended impacts on production or income variability, which can severely constrain adoption.
- **Access to technology:** Adoption may well be constrained in situations in which smallholders have limited physical access to the technology (such as the seeds of improved crop or pasture varieties).
- **Technical know-how:** Some interventions require high levels of technical knowledge about their implementation and management, which may act as a powerful deterrent to adoption.
- **Temporal trade-offs:** Sometimes trade-offs may need to be made in the short term to realize medium- or longer-term benefits (for instance, 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 materialize.
- **CSA trade-offs:** In some situations, some interventions may involve trade-offs among the three CSA pillars (that is, the production, resilience, and mitigation objectives). Productivity-enhancing technology (such as adding nitrogen fertilizer, under some circumstances) may, for instance, increase resilience by improving household cash flow but at the same time increase GHG emissions or their intensities.
- **Information:** Some interventions have recurring informational needs, such as seasonal weather forecasts.
- **Acceptability:** Some CSA interventions (for example, practices that may affect a location's communal grazing governance or investments in areas with weak land tenure arrangements) may go against sociocultural norms, directly affecting a technology's acceptability in a community.
- **State of evidence base:** Insufficient evidence to make robust statements about the relative climate smartness of different alternatives in differing contexts may indirectly constrain their uptake.

Table 4.2 demonstrates clearly that all interventions are associated with some constraints that may affect adoption, depending on the circumstances. Despite the constraints, all of these interventions may be suitable in some

TABLE 4.2—CONSTRAINTS TO THE WIDESPREAD ADOPTION OF CLIMATE-SMART OPTIONS AVAILABLE TO SMALLHOLDERS IN MIXED CROP-LIVESTOCK SYSTEMS IN DEVELOPING COUNTRIES

Option	Constraint									
	Investment cost	Input and operating cost	Risk	Access to technology	Technical know-how	Temporal trade-offs	CSA trade-offs	Information	Acceptability	State of evidence base
Changing crop varieties		*		**				*		
Changing crops		*	*	*	*			*	*	
Crop residue management		*	*			**	*		**	
Crop management		*	*					**	*	
Nutrient management		**			*	*	*			
Soil management	*	*			*	*	*			
Changing livestock breed	**	*	*	*	**	*		*	**	*
Manure management	*(*)			*	**		*	**	*	**
Changing livestock species	**	*	*	*	**	*		**	**	*
Improved feeding	*	**		*	*		*	*	*	
Grazing management	**	*		*	**	*	*	**	*	
Altering integration within the system	*		**		*	**	*	**	**	**
Water use efficiency and management	**	**		*	*	*	*		**	
Food storage					*			*	*	**
Food processing	*	*			*		?		*	**
Use of weather information				*	*	*	*?	*	*	**
Weather-index insurance	*		*	**	**	*	*?	**	*	**

Source: Authors' evaluation. CSA options from FAO (2013).
Note: Importance of constraint: ** = major; * = moderate; ? = unknown or highly context specific. CSA = climate-smart agriculture.

circumstances, but currently there is only limited information concerning the potential uptake of CSA interventions at scale, in terms of geographic or other domains.

Toward Prioritizing Investments in Climate-Smart Agriculture in Africa South of the Sahara

One preliminary step toward generating the information needed to prioritize investments in CSA is to identify those locations where different interventions may be profitable and feasible for smallholders given their biophysical, informational, and socioeconomic constraints. As an illustration, we mapped the 17 interventions outlined above to spatial domains in SSA based on the mixed-system classification shown in Figure 4.1. We used the potential impacts of each intervention from Table 4.1 and the nature of the constraints to adoption from Table 4.2 to subjectively evaluate the suitability of each intervention as 0, low, medium, or high in each system. One way to evaluate suitability is to look at potential adoption rates. To date, adoption rates of agricultural technology in SSA have not often exceeded 30 percent over one or two decades (Thornton and Herrero 2010). Accordingly, we used a potential adoption rate of 5 percent (low suitability), 15 percent (medium suitability), or 30 percent (high suitability), nominally for the period to 2030, for each of the 17 CSA interventions. For each intervention, we calculated the size of the rural area and the current number of rural people in each system, crudely multiplied this by the associated adoption rate, and summed the results to give a highly approximate indication of the relative size of the "suitability domain" (in terms of geographic size and rural population) for each intervention. Results are shown in Table 4.3.

Improved feeding and altering the enterprise balance may be suitable over relatively large areas and for large numbers of people living in rural areas, not all of whom are engaged in agriculture, of course (Lowder, Skoet, and Singh 2014). Food storage, grazing management, and changes in livestock species (particularly from large to small ruminants or from ruminants to nonruminants) 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 those related to increased food availability, but also resilience and mitigation benefits, burdened with only moderate (rather than major) technical and informational constraints (Table 4.2). Considerable effort and resources might well be warranted to increase the uptake of simple food storage technologies and the availability of appropriate information.

Table 4.3 also reveals some interesting differences among systems. The crop-related options generally have higher potential in the intensifying mixed systems, as might be expected. In the extensive mixed (agropastoral) systems, the social acceptability of changing livestock breeds may be a big constraint, with the new breeds offering considerably less potential in these systems than in the intensifying mixed systems, where increasing market orientation may be modifying traditional views on livestock's role

TABLE 4.3—AGRICULTURAL SYSTEM DOMAINS WHERE CLIMATE-SMART OPTIONS MAY BE SUITABLE FOR SMALLHOLDERS IN MIXED CROP-LIVESTOCK SYSTEMS IN AFRICA SOUTH OF THE SAHARA

CSA option	"Suitability"		Total area (in million km^2)	Total rural population (2000, in millions)
	EM	IM		
Changing crop varieties	1	3	0.67	60.62
Changing crops	2	3	1.12	85.78
Crop residue management	0	1	0.07	8.01
Crop management	1	2	0.45	36.60
Nutrient management	1	2	0.45	36.60
Soil management	1	2	0.45	36.60
Changing livestock breed	2	3	1.12	85.78
Manure management	2	2	0.91	61.76
Changing livestock species	3	2	1.59	99.50
Improved feeding	3	3	1.81	123.52
Grazing management	3	2	1.59	99.50
Altering integration between crops & livestock	3	3	1.81	123.52
Water use efficiency and management	2	1	0.76	45.75
Food storage	3	2	1.59	99.50
Food processing	1	2	0.45	36.60
Weather information	3	1	1.45	83.49
Weather-index insurance	2	2	0.91	61.76

Source: Population data from CIESIN (2005). Suitability ratings are the authors' own estimates. CSA options from FAO (2013).

Note: Relative suitability: 0 = not suitable; 1 (low) = 5 percent potential adoption; 2 (medium) = 15 percent potential adoption; 3 (high) = 30 percent potential adoption. EM = extensive mixed systems; IM = intensifying mixed systems (from Herrero et al. 2009; see Figure 4.1). CSA = climate-smart agriculture.

in livelihood systems. Similarly, nutrient management options may have substantial input and operating costs, particularly related to labor, so their potential in the extensive mixed systems is likely to be low, but they show higher potential in the intensifying mixed systems. It is worth noting that some of these potentials may already be changing as climate-targeted financing becomes increasingly available for adaptation and mitigation purposes. From the mitigation perspective, livestock may well be an increasing priority because of their high emissions and also their considerable potential to reduce the emissions intensity of livestock products in SSA, principally through improved diets (Thornton and Herrero 2010).

There are several obvious weaknesses with this analysis: 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 interventions). Nevertheless, this type of broad-brush analysis, if done on a regional basis in relation to specific interventions and with as much quantifiable information as possible, could be very helpful as a first step in prioritizing investments in CSA over the next few years.

Conclusions

The analysis presented here is largely qualitative because at present we lack comprehensive information on the costs, benefits, synergies, and trade-offs of many of the interventions examined. This lack of information is partly because the current state of science for CSA in the mixed systems in SSA is sparse, notwithstanding the efforts of Rosenstock and colleagues (2016) to seek out information through a very extensive review of the literature. There are gaps in our understanding of some of the key biophysical and socioeconomic interactions at the farm level. At the same time, we do not lack for analytical tools and methods that could be used for quantitative priority setting to help allocate the resources needed to stimulate widespread adoption of CSA. To overcome the dearth of field-based evidence on CSA practices and their interactions, modeling tools for the ex ante evaluation of these practices will be particularly useful in these early stages of CSA programming. The outputs of these models can in turn be used to help specify the biophysical relationships in bioeconomic models suited to the ex ante assessment of CSA practices. Although such assessment is important, field-based research and ex post analyses of the adoption of interventions and their economic impacts will also be needed to expand the evidence base as to what works where and why.

Despite the limitations of the analysis presented here, some conclusions can be drawn. First, from a technical perspective, there are no "silver bullets" for climate smartness in the mixed systems. Though this statement echoes the conclusions of the semiquantitative analysis in Thornton and Herrero (2014), the present analysis looked at a much wider range of possible interventions. Table 4.1 indicates that triple wins undoubtedly exist (for example, certain nutrient management practices, changing livestock breeds, and improved ruminant diets can all lead to productivity gains, increased resilience, and mitigation benefits compared with business as usual, in some situations). But technical recommendations over broad domains covering 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 constraints may involve investment or running costs, access to technology and knowledge of how to implement it, social acceptability, or local governance issues. In different contexts, these concerns may conspire to prevent the incremental and transformational shifts toward CSA that may be needed.

Third, some of the interventions evaluated present significant trade-offs between shorter-term food production or food security objectives and longer-term resilience objectives. Such trade-offs apply particularly to crop residue management and altering the integration of crops and livestock within the system, but also to several other interventions (nutrient, soil, and 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, making the triple wins these interventions promise sometimes elusive.

Fourth, the analysis has highlighted several CSA options for which the evidence base is severely lacking. Food storage and food processing appear to have relatively few constraints, although their impacts are uncertain and largely unquantified. As noted previously, these options appear to be heavily under-researched and would benefit from well-targeted research efforts. For these options, as for the use of weather information and weather-index insurance, the evidence base as to their impacts is weak, highlighting the need for robust impact studies that can help guide future research-for-development investment.

Despite some key knowledge gaps, the lack of a silver bullet, 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. Although more comprehensive information could help target interventions more effectively and precisely, in many situations appropriate information already exists, for example, regarding interventions that fit well within current farming practices and do not significantly increase labor demands and household risk. Evidence is also accumulating of the kinds of approaches that can support the scaling up of CSA interventions. Multistakeholder platforms and policy making networks are key, especially if paired with capacity enhancement, learning, and innovative approaches to support farmers' decision making (Westermann, Thornton, and Förch 2015). Modern information and communications technology offers efficient and cost-effective ways to disseminate and collect information at a massive scale, as well as an infrastructure for developing and utilizing new and diverse partnerships. A certain level of local engagement may still usually be needed, paying attention to farmers' needs and their unique situations (Westermann, Thornton, and Förch 2015).