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# Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa

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**Mixed crop–livestock systems are the backbone of African agriculture, providing food security and livelihood options for hundreds of millions of people. Much is known about the impacts of climate change on the crop enterprises in the mixed systems, and some, although less, on the livestock enterprises. The interactions between crops and livestock can be managed to contribute to environmentally sustainable intensification, diversification and risk management. There is relatively little information on how these interactions may be affected by changes in climate and climate variability. This is a serious gap, because these interactions may offer some buffering capacity to help smallholders adapt to climate change.**

Mixed crop–livestock systems, in which crops and livestock are raised on the same farm, occur very widely in the tropics. In sub-Saharan Africa, the vast majority of the mixed systems are rain-fed, and cover large areas of the arid–semi-arid and humid–subhumid zones from Senegal in the west to Ethiopia in the east, and down the eastern side of the continent to South Africa (Fig. 1a). The mixed systems also extend to the tropical highlands of East Africa and southern Africa[1,2], where agro-ecology also permits a higher level of crop diversity (Fig. 1b). In well-integrated 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. Such mixed farming systems form the backbone of African agriculture and provide most of the staples consumed by many millions of poor people in Africa: between 41 and 86% of the maize, rice, sorghum and millet, and 90% of the milk and 80% of the meat[3,4]. These systems are critical for future food security too; population to the end of the century in Africa is projected to quadruple, and 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[3]. At the same time, the mixed systems could play a critical role in mitigating greenhouse gases from the agriculture, forestry and land-use sectors. Mixed crop–livestock systems in Africa are a critical source of protein (Fig. 1c) but are also a considerable source of greenhouse-gas emissions, accounting for 63% of the emissions from ruminants[4]. Nevertheless, the emissions intensities (the amounts of greenhouse gases emitted in kg of $CO_2$-equivalents ($CO_2$e) per kilogram of product) of the mixed systems are 24–37% lower than those of grazing systems in Africa[4], mostly because of the higher-quality diets of ruminants in the former compared with the latter systems. At the same time, these systems provide 15% of the nitrogen inputs for crop production via manure amendments[5].

## Interactions in mixed crop–livestock systems

Mixed crop–livestock systems can be characterized as "farming systems that to some degree integrate crop and livestock production activities so as to gain benefits from the resulting crop–livestock interactions"[6]. The justification for integrating crop and livestock activities is that crop (livestock) production can produce resources that can be used to benefit livestock (crop) production, leading to greater farm efficiency, productivity or sustainability[6]. These resources may be in the form of feed biomass (such as crop residues), manure, power and cash. "Crop–livestock interactions are thus the manifestation of exchange, with the agro-ecological and economic contexts, combined with producers' personal and socioeconomic circumstances, determining the motivation for, form and extent of such exchange"[6].

Crop–livestock integration can then be viewed in four dimensions; space, time, ownership and management (Table 1). In space, crop and livestock activities may be physically close to one another or co-located in a plot or field. In an African context, the degree of integration will usually decrease as area increases because of the constraints of movement of manure, crop residues or livestock, and be highest at the plot or field level. In time, crop and livestock activities may occur simultaneously and be highly integrated, or in sequence or otherwise separated in time, although storage and transport of resources can again increase the level of integration in time as well as in space. The ownership dimension describes the degree to which access to, and control of, the assets used in multiple enterprises are concentrated in the same hands; integration may arise through renting, borrowing and other exchange relationships. The management dimension relates to the fact that management of crop and livestock enterprises may not be in the hands of the same individual or group. Integration along the management dimension, with or without ownership integration, may create additional opportunities for beneficial crop–livestock interaction or allow these interactions to be more efficient[6]. This framework has been simplified for commercial Australian conditions[7], but in its general form it provides a useful way in which to think about crop–livestock interactions, how they may be affected by climate change, and how modification may contribute to adaptation through such aspects as livestock mobility and provision of alternative feed resources.

Mixed systems have long been seen as one stage in an evolutionary process of intensification via increasing human population pressure on a relatively fixed land resource[8]. This is shown as trajectory 1 (refs 9,10) in Fig. 2. At low human population densities, production systems are extensive, with high availability of land and few direct crop–livestock interactions. As population density increases, crop–livestock interactions increase as intensification leads to initial increases in crop and livestock productivity. In the later stages of integration, population density and land fragmentation lead to farm sizes that are no longer viable for maintaining livelihoods from farming activities.

This has several repercussions. First, off-farm income tends to increase in these systems to the extent that it can become the main source of income. Second, soils become heavily degraded in the

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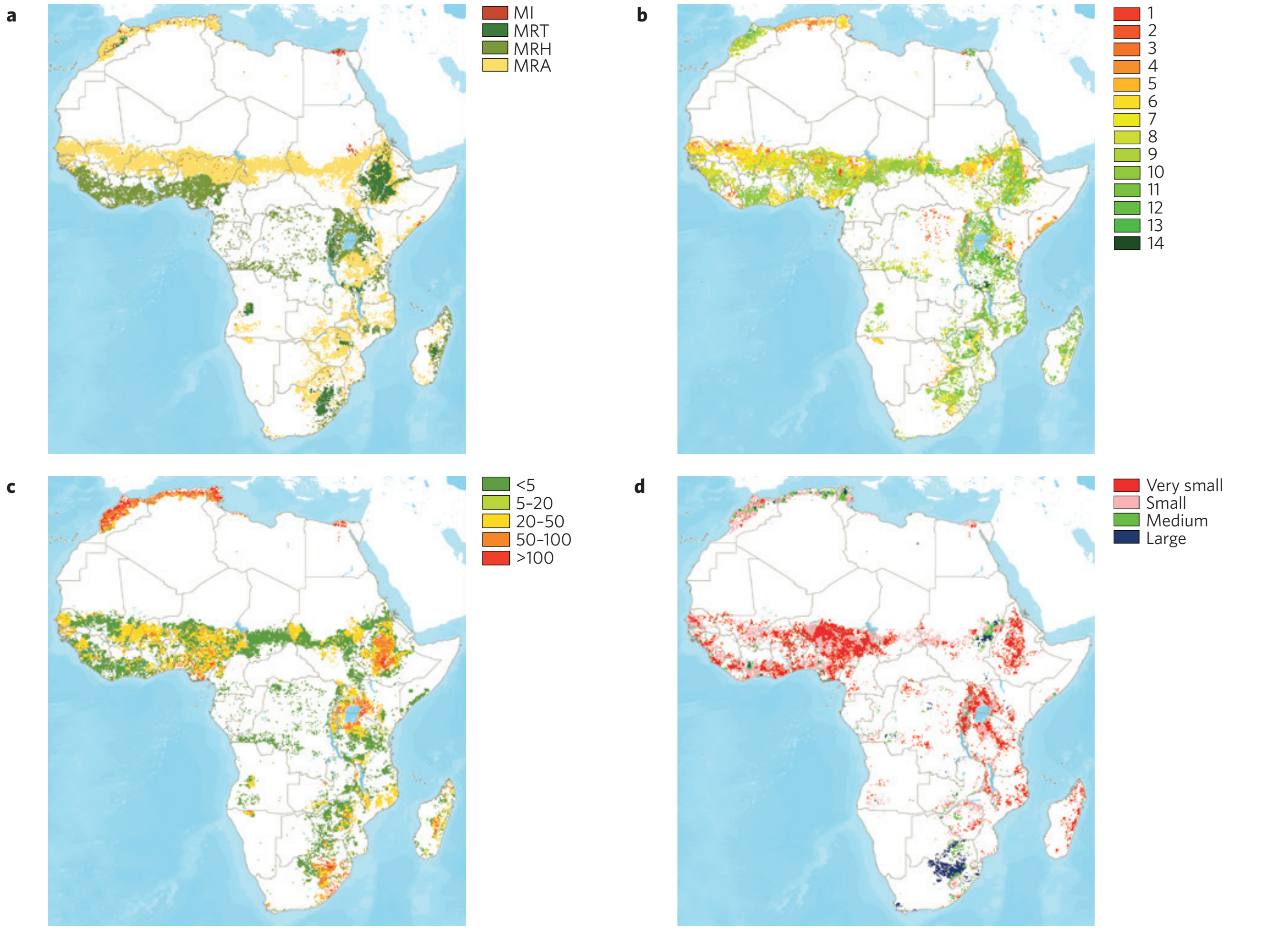


**Figure 1 | Mixed crop–livestock farming in Africa. a**, Types of mixed crop–livestock farming systems in Africa: MRA, mixed rainfed arid–semi-arid; MRH, mixed rainfed humid–subhumid; MRT, mixed rainfed tropical highland; MI, mixed irrigated. The classification is from ref. 1 as mapped in ref. 2. **b**, Crop diversity in the mixed crop–livestock farming systems in Africa, measured as the number of crops (out of 14) in each pixel in the Spatial Production Allocation Model (SPAM) data set in ref. 67. Data are for the year 2000, and include 14 food crops or crop groups: banana and plantain, barley, beans, cassava, groundnut, maize, millet, other pulses (such as chickpeas, cowpeas, pigeon peas and lentils), potato, rice, sorghum, soybean, sweet potato and yam, and wheat. **c**, Protein supply from all livestock sources per person per day (g per person per day) in the mixed systems. Livestock data from ref. 4: production of bovine milk, bovine meat, sheep and goat milk, sheep and goat meat, pork, poultry and eggs, for the year 2000. Protein availability per person per day from edible animal products, including milk and meat from ruminant species (bovines, sheep and goats) and meat and eggs from monogastric species (pigs and poultry), from data in ref. 4, with human population data from ref. 68. **d**, Field size in the mixed systems; data from ref. 16.

absence of fallows and the necessary nutrient amendments, making some of these systems in so-called high-potential areas unresponsive to intensification practices such as the use of fertilizers. Third, relative capital, land and labour costs push these systems towards specialization in production (and thus reduced crop–livestock integration), with typical shifts occurring from food–feed–livestock systems to more cash-oriented activities, with or without livestock[11,12].

Some of these dynamics can lead to producers leaving agriculture as a transformative strategy; but further intensification may be driven by processes of organization that lead to exchanges and market-mediated interactions between different producers who may be widely separated geographically ('area-wide integration'). This is common in parts of Asia, for example, where manure and crop residues for animal feed may be transported very long distances[3]. Other factors may heavily modify this intensification process, such as environmental characteristics, economic opportunities, cultural preferences, climatic events, lack of capital to purchase animals, and labour bottlenecks at key periods of the year that may prevent farmers from adopting technologies such as draft power[11].

Various other trajectories are possible. The mixed systems may diversify to deal with system stressors (trajectory 2 in Fig. 2); this is happening in many places where both land and financial resources are scarce (such as in western Kenya[13]). As growing seasons are projected to shorten in parts of Africa, it is possible to postulate reversal of the intensification process to more extensive crop and/or livestock production (trajectory 3, Fig. 2), although agricultural system transitions in some of the marginal areas of East Africa, for example, seem to be more complicated[14]. A fourth trajectory (number 4, Fig. 2) would see no evolving processes at all, merely persistence of subsistence agriculture and opportunistic cropping as and when this is possible; examples of this have been documented among the Pokot people in semi-arid northwestern Kenya in recent times[14]. In some of these cases, the introduction of cropping into the grazing system improves overall land management and reduces overgrazing.

Probably these trajectories are occurring at the same time, even within the same place in some situations, as pressures build up for transformative changes such as exit from farming and/or land consolidation, as has been observed in other parts of the world in recent

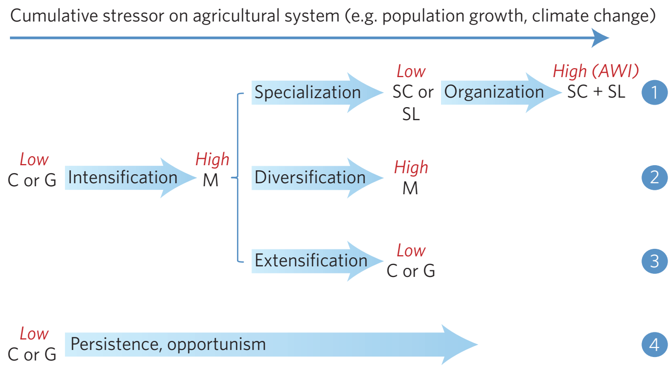


**Figure 2 | Four possible trajectories of crop and livestock systems.** Numbers in blue circles are referred to in the text. C, crop system; G, grazing system; M, mixed system; SC, specialized crop system; SL, specialized livestock system. Red text indicates the degree of crop–livestock integration. AWI, area-wide integration.

decades, such as in the North American and Australian rangelands[15]. At the same time, structural constraints may impede some of these trajectories. For example, the mixed systems in sub-Saharan Africa are characterized in many places by small or very small field sizes (Fig. 1d)[16]. Field sizes may continue to decline, particularly in the higher-potential areas[13]. This may severely constrain the possibilities for intensification or increased production and productivity in the future.

## Mixed crop–livestock systems in a changing climate

Considerable research has been undertaken over the past 50 years on farming systems in Africa. Indeed, 'farming systems research' was invented as a diagnostic process for understanding African (and Latin American) farming households and their decision-making[17]. Despite its rich history, a systems perspective has been largely absent in recent regional and global assessments of agriculture[18]. The Fifth Assessment Report of the IPCC, for example, is heavily oriented towards crops, with separate pieces on livestock, aquatic systems and forestry. Of course, assessments can only assess what has been published: the paucity of information on systems impacts is a reflection of the amount of quantitative work that has been done and that can be harvested for inclusion in such assessments. There may be good reasons for the lack of information at the systems level, including the difficulty of modelling crop and livestock impacts at appropriate spatial and temporal scales, and the vastly different contexts within which smallholders operate and make decisions, not only biophysically but socioeconomically and culturally. Nevertheless, this is a serious knowledge gap, as we attempt to demonstrate below.

The synergies between cropping and livestock husbandry offer various opportunities for raising productivity and increasing efficiency of resource use, thereby increasing household incomes and securing availability and access to food. These are summarized[19] in the context of West African mixed farming systems, relating to the interactions in Table 1: crop residues, manure, power and financial resources. Of a wide range of benefits, local integration of cropping with livestock systems can reduce resource depletion and environmental fluxes to the atmosphere and hydrosphere, offer more diversified landscapes that favour biodiversity, and increase system flexibility to cope with socio-economic and climate variability[20].

Although there are several benefits to mixed farming systems, there may also be disadvantages in some situations, including constraints to increased crop–livestock integration, one of which is that these systems can be complex to operate and manage[21,22]. The positives and negatives of mixed crop–livestock systems are summarized

**Table 1 | Importance of four dimensions of integration for various types of crop–livestock interaction.**

| Crop–livestock interaction | Relative importance of closer integration | | | |
|---|---|---|---|---|
| | Space | Time | Management | Ownership |
| Crop residue | *** | ** | ** | * |
| Manure | *** | * | ** | * |
| Power | *** | *** | * | * |
| Financial resources | * | ** | * | *** |

Data from ref. 6. *Low importance; **some importance; ***high importance.

in Table 2. Many of the factors shown may be positive in one context and negative in another, and even in the same context there may be positive and negative elements in relation to the farming system. This highlights the complexity of mixed systems and the difficulties associated with making broad statements about what works and what does not: local context and the perceptions and objectives of individual farmers may change everything.

Summaries of the projected impacts of climate change on crops in Africa have been published in recent meta-analyses[23–25]. Impacts on livestock in Africa have been summarized[26,27], as have impacts on livestock systems in Africa[28], for example. Although much is known about the different elements that go to make up mixed crop–livestock systems in different parts of the world, much less is known about the possible impacts of climate change on these systems, particularly if the crops and livestock are relatively highly integrated. In investigating how historical trends in Uganda have influenced the adaptive capacity of farming systems, it has been found that trade-offs are made between components of the farming system, and that these trade-offs can influence the subsequent adaptive capacity of the farming system[29]. Shifts from traditional to more modern farming practices can decrease the diversity of the farming system and consequently reduce adaptive capacity, for example. Similarly, the key roles of both crop and livestock assets have been illustrated in farming systems in the Lake Victoria basin[30]. Once asset stocks start to decline because of climate-induced or other stressors, household vulnerability can increase rapidly. Downward spirals of asset loss lead to discernible adaptation deficits and recurring patterns of hardship. Asset loss can be triggered very rapidly, not only by system stressors but also because of cultural imperatives (for example the need for cash to cover funeral expenses[31]). To understand climate change impacts across space and through time, and the farm-level trade-offs that may result, crop and livestock activities cannot be looked at in isolation.

In the future, the mixed systems in Africa will face increasing climate challenges. Figure 3a shows areas of the mixed systems that are projected to undergo two 'flips' by the 2050s. One of these is the number of reliable crop-growing days (RCGDs) going from more than 90 currently to fewer than 90 per year (grey). RCGD estimates the total number of reliable growing days over multiple seasons for those regions with more than one cropping period, and it also incorporates the changing probability of crop failure[32–34]. An indicator rain-fed crop such as maize is considered marginal in areas with fewer than 90 RCGDs[33,35], so the threshold chosen represents the flip from 'suitable' to 'marginal' conditions. The second flip relates to maximum temperature during the primary growing season, going from below 30 °C currently to greater than 30 °C (blue). This temperature threshold was chosen because the growth and yield of several staple crops are adversely affected at temperatures much greater than this[36]. These projected changes in the mixed systems to the 2050s have major implications for agricultural production, and either or both of these thresholds are projected to be crossed in about one-quarter of the mixed systems of sub-Saharan Africa by

**Table 2 | Positives and negatives of mixed crop–livestock systems.**

| Factor | Positive aspect | Negative aspect |
|---|---|---|
| Trade and price fluctuations | Act as a buffer | Need high levels of management skill ('double expertise')<br>Fewer economies of scale |
| Weather fluctuations | Buffer against weather fluctuations | May increase risk of disease and crop damage |
| Erosion | Control erosion by planting forages | Cause erosion through soil compaction and overgrazing |
| Nutrients | Improved nutrient cycling because of direct soil–crop–manure relations | Increased nutrient losses through intensive recycling |
| Draught power | Allow larger areas to be cultivated and more flexible residue management<br>Allow more rapid planting | Extra labour (often women) required for weeding increased area |
| Labour | | Continuous labour requirements |
| Income | Diversified income sources<br>More regular income streams | |
| Investment | Provides alternatives for investment | Requires capital |
| Crop residues | Provides alternative use for low-quality roughage<br>If mulched, controls weeds and conserves water | Feeding competes with other uses of crop residues (for example mulching, construction, nutrient cycling) |
| Security and savings | Provides security and a means of saving | Requires investment |
| Social function | Confers prestige | Cause of conflict |

Data from ref. 21. Note that some factors may be mostly positive or mostly negative, depending on the context.

then (orange indicates that both flips are projected in the same area).

In addition to changes in climate, changes in climate variability are also projected for the future[37]. African smallholders already have a wide range of ways of coping with climate variability[38,39]. Nevertheless, the mixed systems in Africa are characterized in many places by relatively variable rainfall amounts, as estimated by the coefficient of variation of annual rainfall (Fig. 3b)[40]. In the more marginal areas, high rainfall variability already results in substantial production risks, and as rainfall variability is projected to increase into the future, these risks will likewise increase[41]. Impacts of changing climate variability on the mixed systems and on the interactions between crops and livestock are largely unknown.

At the level of the farming system, neither the impacts nor the different responses of crop–livestock smallholders to climate change have been comprehensively evaluated yet. The range of risk-coping strategies currently used by farmers is well documented, but there is increasing evidence that these may not be sufficient over the longer term. A range of innovative ideas around climate services, insurance products and other safety nets is being explored (and in some cases, scaled up) in Africa[42], including the notion of bundles of different options. Analyses have been undertaken that explicitly evaluate some of the trade-offs that can arise at the level of the farming system. For example, trade-offs may arise between the number of livestock that can be supported on a farm and the yields of crops, depending on whether crop residues are fed to ruminants or returned to the soil, either to provide nutrients for subsequent crops[43] or as mulch to help conserve soil and moisture[44]. Other studies have evaluated the trade-offs in use of crop residues in relation to crop yields and feeding animals for draught power[45], and trade-offs in crop productivity, fertilizer use and allocation of labour in smallholder systems[46]. These and other studies have used a range of different methods and tools, including participatory, simulation and optimization approaches, each with distinct advantages and disadvantages[47].

So far, most of the work on trade-offs in the mixed systems has been undertaken in relation to current climatic conditions, and much more analysis is needed to evaluate trade-offs and synergies under climate change, particularly in relation to the availability of resources at the farm level in different local contexts. The availability of labour is one of the key drivers in maintaining the mixed systems of Europe and Australia[48,49]. In the Australian case, declining labour availability has spurred considerable innovation in the way in which crop–livestock farmers manage their mix of enterprises, and allocate land and forage resources in response to climate and price signals (an example is the integration of perennial forages in mixtures with alley- and inter-cropping[49]). Declining farm (and field) sizes and continued urban migration throughout the African continent are already spurring innovation in places, although at the same time, considerable technical, financial and institutional support at both national and local levels will be needed to enhance food security in many of these systems[50–52].

We are not aware of any studies to date that compare the costs and benefits of the range of adaptation possibilities in the mixed systems of sub-Saharan Africa in any comprehensive way. Although research has been done on comparing some adaptation alternatives in relation to criteria such as estimated size of the recommendation domain, adoption potential and production impact, the overall feasibility (and cost) of many adaptation options will depend heavily on local conditions[53].

System adaptation possibilities exist not only at the household level, but also at the landscape level and above. These may come about through induced or autonomous shifts in production system, either at relatively local scales[12] or at broader scales[54], where there may be production benefits (and mitigation co-benefits) from concentrating different systems of production in specific agro-ecological or market-infrastructural zones. For example, transitions from grazing to mixed crop–livestock systems not only could increase global food production, but also could lead to greenhouse gas mitigation owing to more efficient use of land and resources[54]. At aggregated scales, these structural changes may lead to significant reductions in bringing new land into production and to the relocation of production to the areas most suited to it, which in turn could lead to land sparing in some places.

## Assessing adaptation potential

In Africa, the mixed crop–livestock farming systems and the people who live in them will be particularly challenged in the coming decades by climate change, through increasing temperatures, changes in the start and length of growing seasons, and increasing climate variability. In places they will also face considerable and increasing labour and

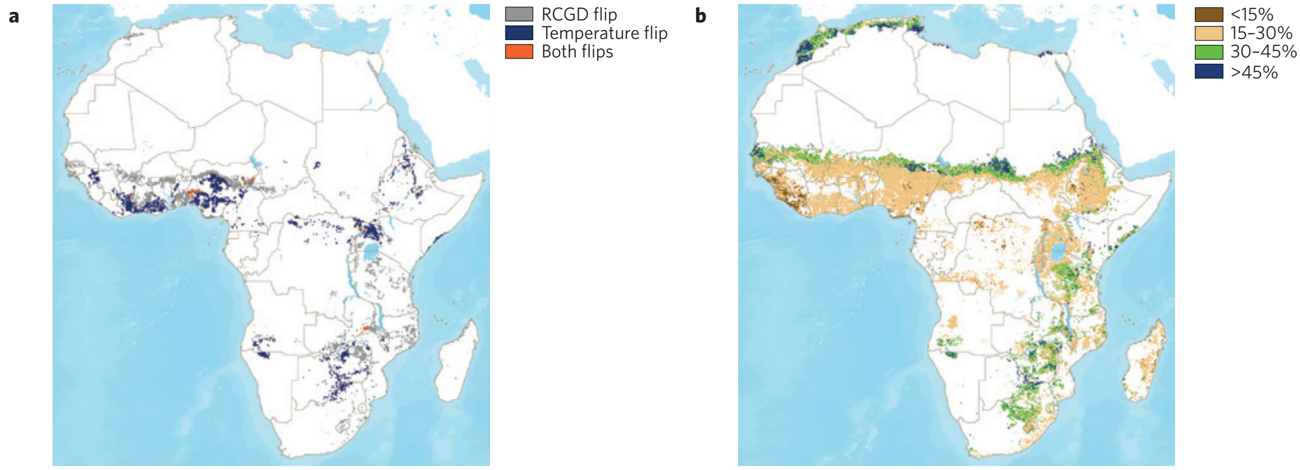


**Figure 3 | Future climate challenges for mixed systems in Africa. a**, Areas of the mixed systems projected to undergo threshold flips by the 2050s: the number of reliable crop-growing days (RCGDs) flips from more than 90 to fewer than 90 per year (grey); maximum temperature during the primary growing season flips from below 30 °C to greater than 30 °C (dark blue); both (orange). Ensemble mean projections of 17 CMIP5 GCM outputs for RCP8.5 and the 2050s. RCGD estimates the total number of reliable growing days over multiple seasons for those regions with more than one cropping period. It also incorporates the changing probability of crop failure. Thresholds and methods are based on refs 32–34. **b**, Coefficient of variation of annual rainfall (%) in the mixed systems. Simulated using the methods in ref. 40.

land constraints. There is enormous diversity in the mixed systems, in relation to their current characteristics and the climate challenges posed (Figs 1 and 3). To target bundles of adaptation options that are locally appropriate but amenable to large-scale investment and scaling up, evaluation of options at the farm scale are needed. To do this effectively, several things need to be in place so that adaptation alternatives can be appropriately assessed in these integrated systems.

**Appropriate biophysical models.** We need appropriate biophysical models that can represent the interactions between crops and livestock adequately, so that evaluations of the mixed systems are more robust. In contrast to earlier thinking on the topic (including our own), we are not confident that increasing the complexity of already complex crop and livestock models through strong integration is an appropriate approach; rather, we should be looking for weak integration between robust and well-tested models. In particular, the spatial and temporal dimensions needed provide considerable challenges. Most modelling work has been done on the primary cereals (particularly maize, rice and wheat) and legumes (groundnut, soybean), but more often than not, adaptation will be about adding lesser-known or alternative crops into existing cropping patterns. Models for such crops need to be developed together with models for other important smallholder crops, including perennial crops[55].

**Appropriate whole-farm models.** We need appropriate whole-farm models, because we need to track flows of cash and the interactions of financial and physical resources in the farm household system. There is widespread appreciation of the need for approaches that combine simulation modelling with deliberative processes involving decision-makers and other stakeholders[56]. Trade-offs between the benefits and costs to a range of stakeholders are inevitable, and these need to be quantified. There is also growing appreciation of the need to combine bottom-up, qualitative social research with farmers and communities, and top-down, quantitative biophysical modelling, to gain more in-depth understanding of farming systems and their potential to adapt to a changing climate[57]. Whole-farm modelling at the level of the farming system in African conditions is constrained by a serious lack of systems data, even on such basic variables such as cropland area, livestock numbers, breeds, crop varieties and management information such as planting dates and fertilizer use. Crowd sourcing, mobile telephony and 'citizen science'[58,59] offer intriguing prospects for data collection and monitoring at massive scale to help rectify this situation. Other essential extensions to the household modelling work include life-cycle analyses and value-chain modelling. As the agenda necessarily develops from a focus on agriculture and food security to the whole food system, the roles of different actors in the value chain, all with their climate change impacts, adaptation and mitigation needs, will need to be considered explicitly in order to develop robust adaptation and mitigation plans for food systems. The explicit inclusion of human nutrition with its appropriate metrics, as a key link between human welfare, farm diversity and land use and environmental performance, is also essential. These areas of work are still in their infancy.

**Appropriate scenarios of the future.** The future of smallholder mixed systems in Africa is highly uncertain. One view is that smallholder systems in general must intensify production in a sustainable way[60] and remain a kingpin of food production; another view is that they will become largely redundant as smallholdings are aggregated into much more intensive and specialized systems, following the evolutionary process illustrated in Fig. 2. The Boserupian model, arguing that population changes will largely drive changes in agricultural systems, has been heavily criticized on various grounds[61]. Many different processes are possible, and as noted above, probably multiple processes will occur simultaneously in different parts of the continent, driven by regional and local factors and contexts. Participatory regional, national or local socio-economic scenarios, which may or may not be linked with appropriate future climate scenarios, are a highly effective tool for exploring future uncertainties and decision spaces with stakeholders, as well as providing a platform for using the outputs from such work[12,62]. The formulation of national visions of how these systems might evolve, supported by relevant policy documents on adaptation actions, may be heavily influenced by the outcomes from such processes, and the adaptation agenda could be advanced significantly thereby.

**Appropriate measures of adaptation success.** What will adaptation success actually look like in the mixed farming systems of sub-Saharan Africa? Vulnerability and adaptive capacity cannot be directly observed, hence the dependence on sets of indicators[63]. Many have been proposed, although a recent systematic review[64] concludes that it is not possible to identify empirically supported patterns of climate vulnerability determinants in the literature. Instead, an approach is proposed that tracks vulnerability and adaptive capacity using a set of indicators that combine objective asset or poverty measures at the household level with more subjective governance and policy factors at the community and national levels[64]. There is ongoing activity in defining appropriate metrics for climate-smart agriculture[65,66]. Indicators are very much needed, not least to be able to identify when farming system adaptation is not enough and much more transformational approaches are needed. Such information is critical when looking into the future to try to guide adaptation planning and investment.

The full adaptation potential of African smallholder mixed farming systems is not yet known, although from a technical standpoint, there is likely to be considerable scope for modifying these systems to improve the livelihoods of smallholder farmers, even in the face of climate change. Given the enormous population-fuelled pressures on land and natural resources that will be building up in the coming decades, this is a critical knowledge gap that deserves serious attention. There are considerable uncertainties concerning appropriate economic development pathways and consumption patterns for most of the agriculturally dependent countries of sub-Saharan Africa; but identifying those that balance national policy objectives with enhanced livelihoods and food security could be enormously beneficial for the hundreds of millions of people living in urban and rural settings. We need to improve our understanding of how African farming systems may change and adapt in response to global change, and how policy and governance frameworks can most effectively provide the enabling environment required.

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## Author contributions
P.K.T. and M.H. designed and wrote the paper together.

## Additional information
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## Competing financial interests
The authors declare no competing financial interests.