Climate change adaptation in mixed crop-livestock systems in developing countries

Philip K Thornton[1*] and Mario Herrero[2]

[1] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), ILRI, PO Box 30709, Nairobi 00100, Kenya.
[2] CSIRO, 306 Carmody Road, St Lucia, QLD 4067, Australia.

Abstract

Mixed crop-livestock systems produce most of the world's milk and ruminant meat, and are particularly important for the livelihoods and food security of poor people in developing countries. These systems will bear the brunt of helping to satisfy the burgeoning demand for food from increasing populations, particularly in sub-Saharan Africa and South Asia, where rural poverty and hunger are already concentrated. The potential impacts of changes in climate and climate variability on these mixed systems are not that well understood, particularly as regards how the food security of vulnerable households may be affected. There are many ways in which the mixed systems may be able to adapt to climate change in the future, including via increased efficiencies of production that sometimes provide important mitigation co-benefits as well. But effective adaptation will require an enabling policy, technical, infrastructural and informational environment, and the development challenge is daunting.

Key Words: Resilience, diversification, risk, food security, vulnerability, co-benefits

* Corresponding author, email p.thornton@cgiar.org
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1. Introduction

Mixed farming systems, in which crops and livestock are integrated on the same farm, are the backbone of smallholder production in the developing countries of the tropics (Herrero et al., 2010). They cover 2.5 billion hectares of land globally, of which 1.1 billion hectares are rain-fed 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 under widely disparate climatic and soil conditions. The mixed systems are particularly important for livelihoods and food security, providing most of the staples consumed by poor people: 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). Figure 1 shows the location of the mixed systems, as defined by Seré and Steinfeld (1995) and mapped most recently by Robinson et al. (2011), in developing countries (here defined very loosely as the countries of the Americas between Mexico in the north and Brazil, Paraguay, Bolivia and Peru in the south, all of Africa, and Asia up to latitude 38 °N excluding Japan).

Several factors are driving changes in the demand for food. Human population in 2050 is currently estimated to reach 9.55 billion (UNPD, 2013), with most of the increase projected to take place in developing countries. Substantial regional variations are projected, however: East Asia will be seeing negative population growth by the early 2030s, while population in sub-Saharan Africa will still be growing at 1.6 per cent per year for the rest of this century. At the same time, many areas, particularly Africa and Asia, will see unprecedented urban growth (UNFPA, 2008). Incomes are projected to continue increasing into the future, typically at rates ranging from 1-3 per cent per year (van Vuuren et al., 2009). Population growth has obvious impacts on food demand, and urbanisation and income growth have considerable effects on patterns of food consumption and dietary make-up (Delgado, 2005; Steinfeld et al., 2006). Global food demand is projected to increase by between 60 and 110 per cent to 2050, depending on the assumptions used (Alexandratos and Bruinsma, 2012; Tilman et al., 2011).

Despite the uncertainty as to how food demand will evolve in the future, the mixed crop-livestock systems in general, and in developing countries in particular, will be of critical importance in helping to meet this demand. As an additional challenge, the production response to meeting food demand has to occur in the face of changes in climate and climate variability. Below, we touch on what is known about the likely impacts of climate change on the mixed systems in developing countries. We then review how crop-livestock smallholders might adapt and discuss some of the enabling factors that may be required. We conclude by noting some key knowledge gaps that need to be addressed if sustained adaptation in the mixed systems of the tropics is to be achieved.

2. Impacts of changes in climate and climate variability on mixed systems in developing countries

The impacts of climate change on agricultural and natural systems have been outlined in many places, including IPCC (2007). Thornton and Cramer (2012) provide a summary of impacts on crops, livestock, fish, water and forest resources from a developing country perspective. In brief, higher average temperatures will tend to accelerate the growth and development of plants. Rising temperatures are not uniformly detrimental, however, as they may lead to improved crop productivity in parts of the tropical highlands where cool temperatures currently constrain crop growth. While average temperature effects are important, other temperature effects may also be critical. For example, increased night-time temperatures have negative effects on rice yields, by up to 10 per cent for each 1°C increase in minimum temperature in the dry season (Welch et al., 2010). Increases in maximum temperatures can lead to severe yield reductions and reproductive failure in crops such as maize, for which each degree day spent above 30 °C can reduce yield by 1.7 per cent under drought conditions (Lobell et al., 2011). Temperature changes may have direct effects on livestock too: most species have comfort zones between 10 and 30 °C, and at temperatures above this, animals reduce their feed intake 3-5 per cent for each 1°C increase (NRC, 1981).

Climate change is already affecting rainfall amounts, distribution, and intensity in many places. This has direct effects on the timing and duration of crop growing seasons and on plant growth. Rainfall variability is expected to increase in the future, and floods and droughts will become more common (IPCC, 2012). Changes in temperature and rainfall regime may have considerable impacts on agricultural productivity and on the ecosystem provisioning services provided by forests and agroforestry systems on which many people depend. Climatic shifts in the last few decades have already been linked to changes in the large-scale hydrological cycle (Dai, 2011). Globally, the negative effects of climate change on freshwater systems are expected to outweigh the benefits of overall increases in global precipitation due to a warming planet.

The atmospheric concentration of CO_2, rising from a pre-industrial value of 280 ppm, has now topped 400 ppm, and has been rising by about 2 ppm per year during the last decade. Many studies show a beneficial effect ('CO_2 fertilization') on C_3 crops and limited if any effects on C_4 plants such as maize and sorghum (Gimenez, 2006). The impact of increased CO_2 concentrations on plant growth under typical field conditions is uncertain, and in some crops such as rice, the effects are not yet fully understood. While increased CO_2 has a beneficial effect on wheat growth and development, for example, it may also decrease the protein concentration in the grain (Taub et al., 2008).

Climate change will affect the quantity and quality of crop residues. Crop residues are a key dry-season feed resource for ruminants in mixed crop-livestock systems, comprising 45-60 per cent of the diets of ruminants in these systems (Blummel et al., 2006). Stover production may not be as affected by climate change as grain yield in some cases: crop failures that result in no grain can still provide substantial amounts of stover. Currently there is only limited information on possible climate change impacts on stover production and quality. Changes in temperature, rainfall regime and CO_2 levels will affect grassland productivity and species composition and dynamics, resulting in changes in animal diets and possibly reduced nutrient availability for animals (McKeon et al., 2009; Izaurralde et al., 2011).

The emergence, spread and distribution of crop and livestock diseases, pests and weeds, may all be affected by climate change, via pathways such as higher temperatures affecting the rate of development of pathogens or parasites, shifts in disease distribution that may affect susceptible animal populations, and effects on the distribution and abundance of disease vectors (Mills et al., 2010; Gregory et al., 2009) and weeds such as *Striga* (Cotter et al., 2012). Disease risks may change for a wide variety of reasons in addition to a changing climate, and there are many unknowns concerning the future status of existing weeds, pests, and crop and livestock diseases and the emergence of new ones.

Aquaculture, a key component of mixed crop-livestock systems in large parts of South and South-East Asia, will also be vulnerable to changes in climate and climate variability. Recent studies in the Mekong Delta have documented several possible impacts. Temperature increases are likely to reduce the breeding rates of some commercial fish species. Increasing frequency of flash floods will probably increase the losses of fish stocks, while more frequent droughts are likely to affect fish populations due to reduced water volumes and changes in water quality (USAID, 2013).

The impacts of short-term weather variability such as droughts and floods on crops and livestock have been widely documented. Increasing climate variability is likely to have substantial impacts on food availability and environmental security for householders in the mixed systems, but the nature of changing extremes and increased weather variability in future, together with their impacts on agricultural productivity and household food security, are largely unknown (Thornton et al., 2014). Nevertheless, the impacts of changes in climate and climate variability on agricultural production will have substantial effects on smallholder farmers in many parts of the tropics and subtropics, and the resulting reduced food security potentially will increase the risk of hunger and undernutrition (HLPE, 2012). While many of the people who are likely to be adversely affected may have only limited capacity to adapt to climate change or to the many other stressors that may affect them, a wide range of adaptation responses is possible. Some of these are outlined below.

3. Adapting to climate change in the mixed systems

Agricultural producers may respond to the threats posed by climate change in different ways; these may be technological, such as the use of more drought-tolerant crops; behavioural, such as changes in dietary choice; managerial, such as implementing different farm management practices; and policy-related, such as market and infrastructure development (IPCC, 2007). There are many ways to classify adaptation options, but here we briefly consider responses that are particularly relevant for the mixed systems, broken down into three types: increasing system resilience, diversification, and risk management. This break-down is somewhat artificial, and there are considerable overlaps between them; for example, the use of a farming system practice such as green manuring may have multiple impacts on increasing resilience to drought and soil erosion as well as on reducing risk through controlling pests and weeds (Kremen and Miles, 2012). The distinction is still useful, however, because the primary focus of these types of adaptation response may be different: risk management is often primarily to do with reducing the variance of an outcome distribution such as household income, and diversification may be more to do with changing both the shape and location of outcome distributions (Thornton et al., 2011). Options to increase resilience may likewise have effects on both the shape and location of outcome distributions, but with a focus on sustainability and on enhancing the ability of agricultural systems to recover swiftly from shocks. The three different types of adaptation options are briefly considered in the following subsections. Given the close relationship between adaptation and mitigation issues in many situations (FAO, 2012), we also include a mention of any important mitigation co-benefits these options may provide in smallholder mixed crop-livestock systems.

3.1 Increasing the resilience of the mixed systems

There are several ways in which the overall efficiency and resilience of crop and livestock production systems can be enhanced in the face of climate change. For example, appropriate soil and nutrient management, through composting manure and crop residues, more precise matching of nutrients with plant needs, controlled release and deep placement technologies, and using legumes for natural nitrogen fixation, can increase the yields and resilience of crops, while reducing the need for synthetic fertilizers (with the co-benefit of reducing the greenhouse-gas (GHG) emissions associated with their use). In situations with decreasing rainfall and increasing rainfall variability, there are many ways of improving water harvesting and retention, through the use of pools, dams, pits, retaining ridges, and increasing soil organic matter to raise the water retention capacity of soils (FAO, 2010). Improving ecosystem management and biodiversity can provide several ecosystem services, leading to more resilient, productive and sustainable systems that may also contribute to reducing GHGs. These services include the control of pests and disease, regulation of microclimate, decomposition of wastes, regulation of nutrient cycles, and crop pollination, for instance. There is often considerable genetic variability in domestic crops and livestock, and characteristics such as ability to withstand temperature extremes, drought, flooding and pests and diseases are often at least partially genetically controlled. The utilization of different crops and livestock breeds and their wild relatives is fundamental in developing resilience to climate shocks and longer-term climate change. Efficient harvesting and early transformation of agricultural produce can reduce post-harvest losses and preserve food quantity, quality and nutritional value of the product. Food processing allows surplus to be stored and sales staggered, and can add resilience to agricultural systems by smoothing food security and income variability.

Changes in agricultural inputs and the way farmers use them may be able to more than offset projected yield declines through the use of some of these options (irrigation water, higher-temperature-tolerant crop varieties and so on) as well as through planting date modifications (Crespo et al., 2011). In addition to positive impacts on the rate of carbon sequestration in tropical systems (Albrecht and Kandji, 2003), the leaves of some tree and legume species can significantly improve the diets of ruminant livestock because of their relatively high nutritive value and digestibility. A ruminant diet that is higher in quality will reduce the methane output per unit of product, so target quantities of animal product can be obtained for lower overall methane emissions and fewer animals (Thornton and Herrero 2010). Trees and legumes on mixed crop-livestock farms can increase the resilience of farming systems by increasing species richness and abundance (Kremen and Miles, 2012) while providing substantial mitigation benefits too (FAO, 2010; Bryan et al., 2013).

The longer-term effects of shocks such as drought on farming systems and livelihoods can be considerable; for households in rural Ethiopia after the 1984-85 famine caused by drought, it took on average 10 years for livestock holdings to recover to pre-drought levels (Dercon, 2004). In these households, livestock holdings were (and still are) enormously important as a form of savings and as a way to accumulate assets. Such shocks can move households into poverty traps from which it is difficult to escape. In these situations, national safety net programmes can play a critical role in helping households to adapt and become more resilient and food secure (FAO, 2012), as can national strategies aimed at stimulating off-farm economic and employment opportunities (Lybbert et al., 2004).

Mixed crop-livestock systems may also provide considerable benefits at the sectoral scale as well as at the household scale. Autonomous, transformational shifts in livestock production from grassland-based systems to more productive mixed crop-livestock systems could substantially increase production efficiencies in many developing countries and decrease market prices, compared with a baseline scenario with no system transitions; in addition, such system shifts could provide important mitigation co-benefits, saving 162 Mha of natural land by 2030 and decreasing GHG emissions by 736 Mt CO_2-eq annually, on a global basis (Havlik et al., 2014).

3.2 Diversification

Diversification may be of different types. Agricultural diversification occurs when more species, plant varieties or animal breeds are added to a given farm or farming community, and this may include landscape diversification – different crops and cropping systems interspersed in space and time. Livelihood diversification may occur when farming households are involved in more and different (non-agricultural) activities, for instance by taking up a job in the city, setting up a shop, or by starting to process farm products. Both agricultural and non-agricultural forms of diversification may be highly relevant for helping to adapt to climate change, in terms of both helping to smooth out short-term household income fluctuations and providing households with a broader range of options to address future change (Thornton et al., 2013).

While diversification can be an important element of climate change adaptation, there is surprisingly limited information available that can be used to guide farmers and farming communities as to how best to manage diversification possibilities. What works in particular situations is highly dependent on the geographical and socio-economic context of the specific farming system. The addition of trees to the farming system may be able to provide smallholders with a broader set of options for securing both food and income (Sunderland, 2011). Crop diversification has been found to be most beneficial in situations where crop growing conditions are neither so marginal that they limit diversification options nor so good as to allow the growing of a single high-return crop (Kandulu et al., 2012). Diversification may also be appropriate in relatively intensive mixed systems such as those of western Kenya, where poverty rates are high, farm sizes are small, and households obtain some 65 per cent of their income from off-farm sources (Waithaka et al., 2006). Climate change is likely to result in highly negative economic impacts on many households in these systems, but the addition of relatively high yielding dual-purpose sweet potato varieties to the farming system, the roots being used for food and the vines as a livestock feed, could partially offset some of these negative consequences. Part of this effect comes about through increased milk production as a result of feeding sweet potato vines to lactating animals (Claessens et al., 2012).

Diet diversification may have an important role to play in adapting to climate change. Some communities in East Africa have been diversifying their diets considerably over the past 40 years, including some pastoral households that have taken up cropping even in marginal places where cropping is very risky (Rufino et al., 2013). In these places, maize and legumes predominate, but some householders are increasing their crop and diet diversity, particularly in locations with annual rainfall higher than 800 mm. In places where maize cropping will become increasingly risky in the future because of climate change, more drought-tolerant crops such as millet, sorghum and cassava may become important for food-insecure households, although knowledge transfer concerning the growing and utilisation of unfamiliar and untraditional crops will be needed (Rufino et al., 2013).

There must be limits as to how far existing agricultural systems can be modified, and thresholds can be envisaged beyond which climate change may be so great that coping ranges and buffering capacities are exceeded. In such cases, ensuring the food security and wellbeing of mixed farming communities may require transformational changes in livelihood strategies and, as noted above, the provision and utilisation of safety nets and/or a broadening of income-generating opportunities, where this is feasible.

3.3 Risk management

While climate change is expected to result in increased climate variability (IPCC, 2012), there are many unknowns regarding the nature of this increased variability. Floods and droughts may lead to complete destruction of crops, while increased frequency of droughts may result in decreased livestock herd sizes because of increased mortality and poorer reproductive performance, severely compromising food security. Increasing climate variability may also have substantial impacts on environmental security, as the potential exists for conflicts over livestock assets and natural resources to escalate in the future.

Options to manage risk can operate at multiple scales. At the field level, intercropping varieties with different phenological traits such as time to maturity can spread the risk of drought spells (Cavatassi et al., 2010). At the farm level, households may engage in mixed crop-livestock farming when weather risks increase: livestock can be used as an asset to smooth income fluctuations and opportunistic cropping can provide dietary calories for households at critical times of shortage (Miura et al., 2012; Rufino et al., 2013).

The use of weather forecasts can lead to decisions that may affect large numbers of people in the landscape, such as the seasonal forecasts for West Africa in 2008 that warned of high probabilities of above-normal rainfall for the July-September rainy season. This information was used by emergency aid providers to increase preparedness and ultimately lives were saved as a result (Tall et al., 2012). Many issues related to the effectiveness of climate forecasts for crop and livestock management remain that need to be addressed, particularly with regard to effective mechanisms for the delivery and utilisation of this type of information, but progress is being made in several countries in sub-Saharan Africa on this front (Hansen et al., 2011).

Another option that can operate at different scales is insurance. A variety of different instruments exists, including weather-indexed insurance (i.e., policy holders are paid in response to ‘trigger events’ such as abnormal rainfall, for example). Weather insurance has been widely trialled and evaluated in parts of India (Giné et al., 2008). National weather-indexed crop insurance was first used in Malawi in 2008, and is still in operation, any payout being used to finance food imports or social safety net programmes in affected areas (FAO, 2012). Recent developments in East Africa in weather-indexed livestock insurance highlight the potential for public-private partnerships in situations where the incentives and risks involved do not make it feasible for the private sector alone. Weather-indexed insurance schemes for individual livestock keepers based on satellite imagery are being piloted in several areas of drought-prone northern Kenya and southern Ethiopia (Chantarat et al., 2012). The widespread uptake of index insurance faces substantial challenges, however, including the issues of basis risk, cost and transparency. Whether index insurance at scale can lead to tangible and sustainable impacts on poverty and food security in general, is a matter of some uncertainty (see Miranda and Farrin (2012) for a recent review).

Refining risk management techniques to make adaptation more effective is likely to include a blend of the old and the new. Farmers in the tropics have a long history of coping with climate variability and have developed many different ways of addressing the issue (Matlon and Kristjanson, 1988). At the same time, there are several new tools and approaches that are now available that can be used to develop and fine-tune climate risk management strategies that are specifically tailored to stakeholders' needs (Hansen et al., 2011).

3.4 Adaptation in the mixed systems: are there "best bets"?

A range of the adaptation options discussed above are listed in Table 1, in relation to their potential impacts on household food security, their potential contribution to household resilience, diversification and risk management, their potential for providing mitigation co-benefits, and some of the constraints to their adoption. Two major points can be made about Table 1. First, there would appear to be no silver bullets: no options stand out that have high potential for enhancing food security and addressing resilience, diversification or risk management, with clear mitigation co-benefits, that do not also have constraints to their adoption in certain (perhaps many) situations. This suggests that all these options will be needed in different circumstances, and that their feasibility will depend on local conditions. Second, there are no alternatives in Table 1 that we judge to have strong impacts on increasing resilience of households: there are limits to what can be achieved in increasing resilience through agricultural management. The importance of the policy and enabling environment with respect to adaptation is obvious, but identifying the bounds of what endogenous adaptation can achieve in relation to incomes and food security in smallholder systems is critical for informing national policy debates.

The points above highlight the need for comprehensive, consistent analysis of the different options available at relevant scales for making appropriate choices. We show an example in Figure 2 for illustrative purposes. This takes a set of different options that were investigated originally for their potential to mitigate greenhouse gas emissions in the livestock systems in the tropics and subtropics (Thornton and Herrero, 2010). Here, we compare several of these options: intensifying the diets of large ruminants through feeding crop residues with an increase in digestibility of 10 percentage points, well within the range of variation in digestibility that has been observed in sorghum, for example (Blümmel et al., 2006); intensifying large ruminant diets via increasing the amount of grain fed as a supplement; intensifying diets via feeding the leaves of *Leucaena leucocephala* as a supplementary feed for cattle; and a shift in breed of dairy cattle from local, low-productivity animals to higher-productivity cross-bred animals. For a simple evaluation framework, we took five criteria: one, the size of the domain throughout the global tropics within which each of these options might be applicable; two, the percentage adoption rate to 2030, based on the best-case historical adoption rates that we could find in the literature; three, the productivity impacts resulting from the adoption of each alternative, here measured in terms of the reduction in livestock numbers needed to meet regional demand for livestock products according to the baseline scenario of the International Assessment of Agricultural Science and Technology (Rosegrant et al., 2009); four, the mitigation potential of each alternative in terms of its potential reduction in methane and carbon dioxide emissions; and five, the feasibility of each option related to the external enabling or disabling environment (issues associated with infrastructure, policy, governance, and the private sector, for example) that would influence its effectiveness in particular situations. For the first four of these criteria, data from the original study were used directly (Thornton and Herrero, 2010). For the feasibility criterion, we made a subjective judgement.

Results are shown in Figure 2. Of the four alternatives considered, the use of higher-digestibility stover and the use of agro-forestry trees for livestock feed have advantages over grain supplementation (a relatively small domain and issues of feasibility) and use of cross-bred dairy cattle for milk production (major issues of feasibility). Improved feeding through the use of agroforestry species can have sizable mitigation benefits too. The planting and utilisation of forage trees and shrubs as a livestock feed supplement are not without issues at the local level -- possible effects on household labour resources and availability of appropriate planting material and management know-how, for example -- but such issues need not be insuperable barriers to the widespread uptake of this technology (Franzel and Wambugu, 2007). Similar analyses as those shown in Table 2 could be undertaken for all the options in Table 1 at global and other scales, but as far as we know this work has yet to be undertaken in any comprehensive way.

4. Enabling adaptation in mixed crop-livestock systems

The increasing demand for food in the coming decades, as a result of population growth, increasing incomes and changes in dietary preferences, will undoubtedly continue to provide a massive opportunity for poverty reduction and economic growth in many developing countries, although the future role of smallholders in this is unclear. In developing countries, smallholder production currently provides food for the great majority of the poor (Herrero et al., 2010). It is unlikely that this will change much in the foreseeable future, although the development of sustainable and profitable smallholder agricultural production is likely to need massive investment, particularly in Africa (World Bank, 2009). In addition to such investment, there are several ways in which an enabling environment can be fostered to help smallholders adapt to climate change (Thornton et al., 2013). Here we touch on four: utilising appropriate tools; fostering innovation; fostering local institutions; and informing policy.

Some of the recent discourse on climate change, development and food security focuses on sustainable intensification (Garnett et al., 2013; FAO, 2012; Foresight, 2011), given that more food will be needed in the coming years and that it will need to be produced without bringing new land into agricultural production by improving efficiency, reducing waste, decreasing GHG emissions, and increasing carbon sequestration. An important implication of this is the necessity of assessing adaptation technologies across multiple objectives, multiple time frames, and multiple spatial scales. Multiple objectives may include food security, enhancing livelihoods and incomes, and reducing GHG emissions, for example. Options need to be evaluated over the short-term as well as the long-term (thus dealing with climate variability as well as longer-term shifts in temperatures, for example), and making sure that what is proposed as well-adapted today does not become maladaptive in the future. Options also need to be evaluated at different scales: there need to be benefits for rural producers as well as for urban consumers, and much adaptation and mitigation can be achieved at the landscape scale through appropriate spatial trade-offs, for example. A key enabling factor is making sure we have appropriate tools at our disposal to design, evaluate and target appropriate technological options. For evaluating mixed crop-livestock systems, there is considerable activity on modelling at scales ranging from the global to the household, although there is still much to do to ensure adequate representation of livestock and crop-livestock interactions in such models (Dumollard et al., 2013).

Evaluating and targeting options that have the potential to meet different stakeholders' objectives is a necessary step, but a key factor in sustained adaptation of agricultural systems is social, institutional and technological innovation, the process by which social actors create value from knowledge (Douthwaite, 2002). Innovation can be fostered through three levers: increasing the pool of new ideas and technology that feed into learning cycles, changing how people interact while innovating and making sense of the results, and changing the ways they measure and select what works and what does not (Axelrod and Cohen, 2000). Greater emphasis can be placed on the second and third of these levers through developing approaches that change the ways in which people interact while innovating and by developing methods that can help people make better and faster decisions about how technology and institutions are working. The methods and approaches of social learning may have much to offer here (Harvey et al., 2012; Kristjanson et al., 2014). One of many possible examples is the use by African farmers of mobile phone technology to engage in participatory plant breeding and varietal selection - crowdsourcing being used to evaluate and distribute seeds that fit their objectives and farming systems (van Etten, 2011).

A third enabler of sustained adaptation is the strengthening of local institutions, both formal and informal (Ickowicz et al., 2012). These can play a key role in facilitating and encouraging agricultural producers to make changes to their production systems and manage natural resources in a way that helps them achieve household food security. Local institutions also have important roles to play in the flow of information (such as weather forecasts and extension materials concerning new technologies, for example) and in the management of communal resources such as grazing and water resources (McCarthy et al., 2011). Evidence from pilots in Africa, some in mixed crop-livestock systems, demonstrates that investing in institutions for the sharing of seasonal forecasts in local communities, and utilising new information technology, can significantly increase the ability of farmers to reduce their exposure to weather risk by altering the way in which they manage their crops and livestock (Hansen et al., 2011). National governments have a key role to play here, along with NGOs and the private sector, in generating and disseminating appropriate information and assembling an evidence base of what works where and why.

Fourth, sustained adaptation will require coordinated and informed policies. In turn, this will require an integrated approach to addressing food security, agriculture and climate change, and addressing the often fragmented policy and institutional architecture that exists at national and international levels – particularly integrating climate change issues into the decision-making processes in ministries of agriculture (Thornton et al., 2013). There are huge challenges in dealing with the uncertainties and addressing the trade-offs and synergies that may arise from different policy actions. This calls for considerable enhancement of the links between science and policy making, and making robust information available in appropriate formats. Tools such as scenarios, which explore multiple plausible futures together with key stakeholders across multiple sectors, have potential for strengthening the science-policy interface, allowing diverse actors to share and combine perspectives, and for providing actionable information (Kok et al., 2006). In East Africa, for example, regional scenarios are being used to engage with national and regional policy-making organisations. All scenarios see an increase in mixed crop-livestock systems, and although these systems will intensify considerably to the 2030s, food demand continues to outstrip supply, so the region will continue to import commodities such as maize (Vervoort, 2013). Policy formulation needs to be not only coherent but also flexible to respond to changing circumstances: regional and international trade, policies that promote food production in the most appropriate areas of a country, and expanded climate finance initiatives such as the Green Climate Fund, all have potential to contribute substantially to adaptation.

5. Conclusions

The mixed crop-livestock systems of the tropics are critical for the current food security of large numbers of people. In view of expected population growth and growth in demand for food in the coming decades, this role is unlikely to change significantly in the foreseeable future, particularly in south Asia and sub-Saharan Africa.

There are considerable gaps in our understanding of how climate change may impact mixed crop-livestock systems in the tropics, particularly the interactions between changes in temperature, rainfall and atmospheric carbon dioxide concentrations and their effect on agricultural productivity, and resultant changes in the incidence, intensity and spatial distribution of important weeds, pests and diseases. Similarly, the impacts of increases in climate variability on the mixed systems and smallholders' food security are largely unknown. At the same time, the prognosis for robust quantification any time soon of changes in weather and climate variability over short temporal and spatial scales is gloomy (Ramirez et al., 2013). This suggests that the impacts modelling community will need to become increasingly creative in asking questions that have actionable answers from the perspective of agricultural decision makers at all levels.

The policy environment within which smallholders operate is likely to change substantially in the future in response to many drivers. Over and above a changing climate, these include the need to move to more intensive, lower-carbon agricultural systems; growing competition for increasingly scarce resources such as water and land; the trade-offs required between agricultural production for human food, animal feed, and biofuels; and the involvement of smallholders in international carbon markets once solutions have been found for the associated institutional issues (Rosegrant et al., 2009). These drivers will have enormous impacts on smallholder mixed farming systems, and better understanding of the likely impacts at the household level will be vital in identifying and targeting the alternatives that can help farmers raise incomes, enhance food security and sustain their natural resource base in the future.

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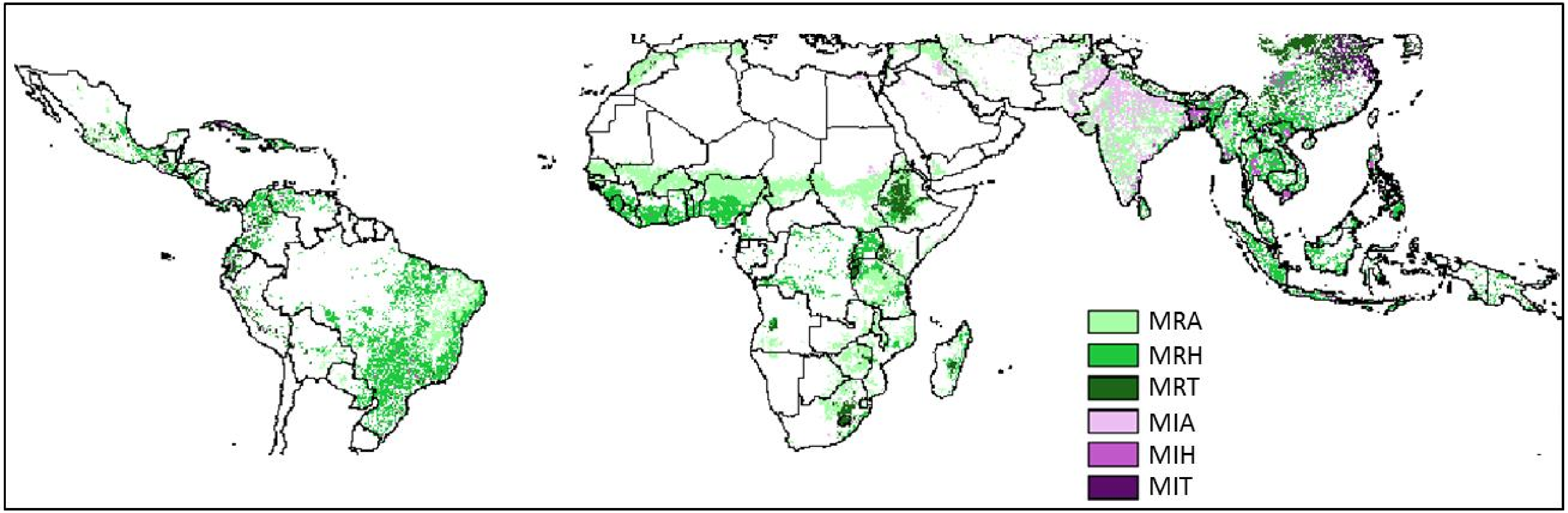
Table 1. Some of the adaptation options available to smallholders in mixed crop-livestock systems in developing countries, their potential for providing mitigation co-benefits, and constraints to their adoption. Based on FAO (2013) with some adaptation and expansion.

Option **(with some examples)**	**Impact on food security**	**Potential impact on resilience**	**Potential to promote diversification**	**Potential for managing risk**	**Potential for providing mitigation co-benefits**	**Constraints to adoption**
Change crop varieties (higher-yielding, stress-tolerant, dual-purpose varieties)	+++	++	+++	+	?	High investment costs, high prices of improved varieties, high costs of inputs
Change crops (higher-yielding, stress-tolerant, dual-purpose crops)	+++	++	+++	++	?	Lack of agronomic knowledge, lack of experience in utilisation of unknown crops
Crop residue management (minimum tillage, cover cropping, mulch)	+	+	+	++	+	Competing demands for crop residue biomass, labour demands
Crop management (modify planting dates, multicrop varieties with different times to maturity)	++	+	+	++	?	Access to appropriate seed, labour demands
Nutrient management (composting, appropriate fertiliser / manure use)	++	++	+	+	++	Cost, limited access to technology and information
Soil management (crop rotations, fallowing, intercropping with leguminous crops / shrubs)	++	+	+	+	++	Limited gains over the short term, labour demands
Change livestock breed (use of improved and/or stress-tolerant breeds)	+++	++	++	++	?	Cost, lack of experience and knowledge
Manure management (composting, improved manure handling / storage / application methods)	+	+	+	+	++	Labour demands, lack of knowledge
Change livestock species (stress-tolerant species)	+++	++	++	++	?	Cost, accessibility, lack of knowledge
Improved feeding (diet supplementation, improved grass and fodder species)	++	+	+	++	+++	High cost, labour demands, lack of knowledge

Option (with some examples)	Impact on food security	Potential impact on resilience	Potential to promote diversification	Potential for managing risk	Potential for providing mitigation co-benefits	Constraints to adoption
Grazing management (adjust stocking densities to feed availability, rotational grazing)	++	+	+	++	++	Labour demands, lack of knowledge
Alter integration within the system (addition / deletion of enterprises within the farming system, changing the ratio of crops to livestock and / or the ratio of crops to pasture, addition of trees / shrubs)	++	++	++	+	+(+)	Lack of information, lack of fit with household objectives
Water use efficiency and management (irrigation to maximise water use; modify cropping calendar)	++	++	+	++	?	Lack of information, cost
Food storage (more efficient storage to reduce post-harvest losses and waste)	++	++	+	++	?	Accessibility to technology, cost, socio-cultural issues
Food processing (drying food destined for sale and primary processing of food crops to add value at the farm gate)	++	++	++	++	?	Accessibility to technology, cost, socio-cultural issues
Dietary shifts (substituting a proportion of maize meal in the diet for sorghum and/or millet meal)	++	++	+++	++	?	Accessibility, socio-cultural issues, lack of knowledge about utilisation
Use of weather information (to modify crop, livestock management)	+	+	+	++	?	Reliability, accessibility, timeliness, lack of knowledge
Weather-index insurance (for crops, livestock)	++	++	+	+++	?	Cost, covariate risk, lack of information, sustainability

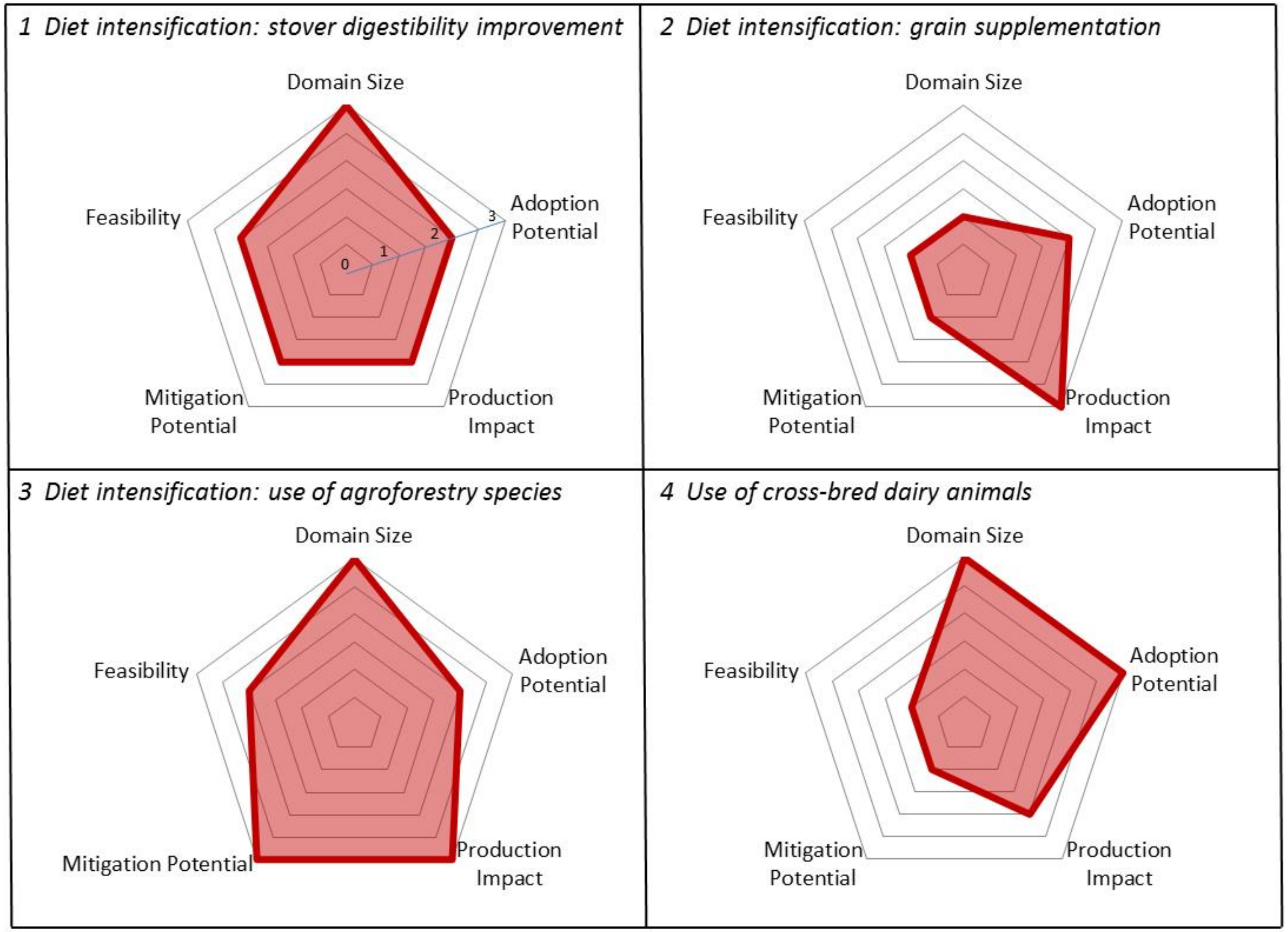
+ less impact/potential, +++ most impact/potential, ? unknown or highly situation-specific

Figure 1. Location of the mixed crop-livestock systems in the tropics and subtropics (from Robinson et al., 2011).



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. Rain-fed mixed systems (MR): those in which >90% of the value of non-livestock farm production comes from rain-fed land use. Irrigated mixed farming systems (MI): those in which >10% of the value of non-livestock farm production comes from irrigated land use. MR and MI are then broken down based on temperature and/or length of growing period (LGP), the number of days per year during which crop growth is possible: Arid and semi-arid (A), LGP ≤ 180 days; Humid and sub-humid (H), LGP > 180 days. Tropical highlands (T): areas with daily mean temperature during the growing period of 5-20 °C. Original classification of Seré and Steinfeld (1995) mapped using proxies by Robinson et al. (2011).

Figure 2. Comparison of four adaptation options in mixed crop-livestock systems in the tropics and subtropics, related to five criteria: size of domain, adoption potential, production impact, mitigation potential, and feasibility. For details and data, see Thornton and Herrero (2010).



1 Diet intensification: stover digestibility improvement

2 Diet intensification: grain supplementation

3 Diet intensification: use of agroforestry species

4 Use of cross-bred dairy animals

All criteria rescaled to relative values of 1, 2 or 3 as follows:

Domain size: 1=low (<300 Mha), 2=medium (300-600 Mha), 3=high (>600 Mha).

Adoption potential: 1=low (<15%), 2=medium (15-25%), 3=high (>25%).

Production impact, expressed as the % reduction in animals possible to meet demand in 2030: 1=low (<14%), 2=medium (14-21%), 3=high (>21%).

Mitigation potential to 2030: 1=low (< 10 Mt CO_2-eq), 2=medium (10-20 Mt CO_2-eq), 3=high (> 20 Mt CO_2-eq).

Feasibility: 1=low, 2=medium, 3=high, qualitative judgement based on the authors' perceptions.