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The Status of Crop-Livestock Systems and Evolution toward Integration

M. Iiyama[1], S. Kaitibie[2], P. Kariuki[2] and Y. Morimoto[3]

[1] *World Agroforestry Center (ICRAF), United Nations Avenue, Gigiri, PO Box 30677-00100, Nairobi, Kenya*

[2] *International Livestock Research Institute (ILRI), PO Box 30709, Nairobi 00100, Kenya*

[3] *Biodiversity International C/o ICRAF, United Nations Avenue, Gigiri, PO Box 30677-00100, Nairobi, Kenya*

Abstract: This article presents the current state of crop-livestock systems in developing countries, and reviews the recent literature on "crop-livestock integration" as an alternative landuse option for agro-pastoralists to cope with the changing environment in Sub-Saharan Africa and other developing regions. Mixed crop-livestock systems are one of the dominant agricultural systems in the developing world. While crop-livestock systems tremendously vary across different biophysical and demographic settings, agro-pastoralists face challenges such as population growth and globalization. Changes in the lifestyles of agro-pastoralists and market access tend to lead to commercialized farming, while population pressures lead to scarcities and degradation of resources for conventional extensive farming. Crop-livestock integration is viewed as an economically feasible and environmentally sound solution for poor agro-pastoralists to achieve sustainable agricultural production. Optimal pathways for crop-livestock integration should achieve the best utilization of locally available resources without much reliance on external inputs through recycling of crop/animal residuals. Although such pathways may be determined by use of systems analysis, it is recognized that the realities of the system are often more complicated than the predicted optimal pathways suggest, due to diversities in agro-ecological, demographic, and market conditions as well as to socio-economic factors. Hence, this review investigates the determinants of crop-livestock intensification and summarizes inferences for future research challenges. It draws the conclusion that crop-livestock integration should be analyzed from a holistic/integrated perspective.

Key words: Crop-livestock systems, crop-livestock integration, system analysis.

The Issues

Crop-livestock farming systems constitute the dominant land use system in developing countries in Sub-Saharan Africa, South and Southeast Asia, and Latin America. In developing regions, mixed rainfed farming zones account for 25% of the total land areas, and accommodate 42% of the total population, 37% of the total cattle and 36% of the total sheep and goats. Approximately 66% of the world's poor livestock keepers are found in these zones (Thornton *et al.*, 2002; Steinfeld *et al.*, 2006). Furthermore, crop-livestock farming systems are of growing importance, not only because existing systems are expanding, but also because formerly specialist livestock or crop production systems are diversifying into crops and livestock, respectively (Mortimore, 1991; Thornton *et al.*, 2002; Steinfeld *et al.*, 2006). Considering their significance on livelihoods of the poor, proper understanding of the mixed crop-livestock systems is critically important in order to devise appropriate technology transfers and institutional reforms for poverty alleviation, food security and sustainable resource management (McIntire *et al.*, 1992; Pell, 1999; Thornton and Herrero, 2001; Kristjanson and Thornton, 2004; Herrero *et al.*, 2007).

Understanding crop-livestock systems is enormously challenging. For example, systems consist of distinctive but tightly interdependent components or sub-systems which are highly heterogeneous across regions depending on agroclimatic and demographic conditions (McIntire *et al.*, 1992; Williams *et al.*, 1999). Furthermore, these systems have been dynamically evolving. Across the developing regions, agro-pastoralists have faced tremendous socio-economic and environmental challenges: i.e. population growth and increasing importance of cash economy, though rates of such changes differ across regions/sub-regions (Delgado *et al.*, 1999; Steinfeld *et al.*, 2006). While involvement in cash economy has necessitated agro-pastoralists to undertake more diversified livelihood strategies and to commercialize crop and animal farming, population pressures have led to growing scarcities and degradation of resources for conventional extensive farming practices (Tiffen, 2004; Williams *et al.*, 2004; Mertz *et al.*, 2005).

What makes the evolution of mixed systems unpredictable is that farmers may pursue multiple objectives (e.g. food security and income maximisation) with multiple system components (e.g. plants and animals). Crop-livestock integration, defined as a process by which farmers intensify their activities by integrating components of crop and livestock activities, is expected to be an economically feasible and environmentally sound pathway for poor agro-pastoralists (Powell and Williams, 1994). Otherwise, there should be competition for resources (e.g. land and labor) between components with destabilizing effects on resource sustainability. If productivity is to increase because of increasing demand and increasing land pressure, then there are real research needs to enhance the complementarities between crop and livestock production (Thornton and Herrero, 2001). The potential for integrated crop and animal production is perceived to be high while further population growth is expected in the next few decades. Hence the need to study the sequences in which interactions contribute to poverty alleviation, food security, and sustainable resource use will remain high (Mortimore, 1991; Kristjanson and Thornton, 2004).

Objectives

The main objective of this review article is to review the current status of the crop-livestock systems in developing countries and the major methodologies applied to analyzing crop-livestock integration, in order to derive policy implications and identify further research challenges.

First, the status of crop-livestock systems in developing countries is outlined. The concept of mixed crop-livestock farming systems is explained and crop-livestock 'integration' in contrast to mere 'diversification' is elaborated. Then, the spatial distribution and diversity of mixed crop-livestock systems across developing regions are reviewed.

In general terms, agroclimatic conditions and population densities tend to define the set of possible crop-livestock components and their specific interactions, whilst socio-economic factors determine the actual farming system that can be observed at a given time (McIntire *et al.*, 1992; Pro-Poor Livestock Policy Initiatives, 2003). Two major socio-economic factors driving evolution of the crop-livestock systems, i.e. population growth and globalisation, are discussed, with regards to dynamics and challenges which have necessitated sustainable intensification and integration of crop-livestock components

Second, the major methodologies recently developed and popularly applied to analyze crop-livestock integration are reviewed. Analytical methodologies are, at a minimum, required to simultaneously deal with multi-dimensional aspects of the systems, i.e., interactions between crop and livestock production; the circumstances promoting the evolution of mixed farming; and interactions between farming activities, off-farm activities and resource management. Though it is difficult to strictly differentiate inherently interdisciplinary arguments concerning crop-livestock integration, we tentatively categorize approaches used in the recent literature into three methodologies, i.e. (1) system analysis approaches to model optimal scenarios on resource flows between system components, (2) empirical studies to identify meso-level factors affecting crop-livestock pathways, and (3) case studies to investigate effects of households' resource endowment and engagement in off-farm activities on the adoption of particular crop-livestock patterns.

The rest of this paper is organized in the following way: the next section elaborates on the definition of mixed crop-livestock systems and their spatial distribution and variations across developing regions. It also describes their dynamics and challenges. The third section reviews the popular research approaches which are applied to systematically analyze multi-dimensional aspects of crop-livestock integration, and discusses their key concepts, methodologies and applications. The fourth section concludes by summarizing the arguments and proposing future research agendas in order to mobilize and consolidate knowledge and expertise in disseminating information and accelerating effective implementation of crop-livestock integration.

Crop-livestock Systems

Definition, spatial distribution and variability in crop-livestock systems

Definition: Smallholder farming sectors in arid, semi-arid, and sub-humid zones in developing countries rarely lack livestock components (Mortimore, 1991; Thorne, 1998). Mixed farming systems are understood to exist where both livestock and crop production take place within the same locality, and where ownership of crops or land and livestock are integrated. Where specialized livestock production takes place in the same locality as crop production, subject to resource-sharing (e.g. grazing of residues), but under separate ownership, such systems are considered as an early stage of evolution towards integrated ownership (Mortimore, 1991; McIntire *et al.*, 1992).

Even under the same ownership, the levels of crop-livestock interaction, defined as using crops in livestock production and vice versa, greatly differ across regions in developing countries due to heterogeneous agroclimatic and demographic conditions and exogenous technological factors (McIntire *et al.*, 1992). Diversification occurs where components co-exist rather independently on the farm. Their combination serves to reduce risks, but their interactions are minimal. Conversely, crop-livestock integration, defined as the merger of the two on one farm, occurs where the components are interdependent (Thorne, 1998; van Keulen and Schiere, 2004).

Even without much integration, diversifying livelihoods into animal production gives security to poor crop farmers facing high climatic risks, because livestock as an asset can be easily liquidated at a time of emergency (Ashley and Nanyeenya, 2005). On the other hand, as population density increases, there is increased demand for integration in order not only to ease competition over resource use between components, but also to exploit their complimentarities (McIntire *et al.*, 1992). The benefits of crop-livestock interactions are several. Animal traction could improve the quality and timeliness of farming operations now done by hand, thus raising crop yields and farm household incomes. Farm animals might provide manure to improve soils. Livestock sales would generate cash to buy inputs. Keeping animals on the farm could also provide a gainful use for other resources such as crop residue, which might be wasted in the absence of animals (McIntire *et al.*, 1992; Thorne *et al.*, 2002; Bationo *et al.*, 2004; Manyong *et al.*, 2006).

Spatial distribution: This section reviews the spatial distribution of crop-livestock systems in developing countries. Agroclimatic and demographic factors are the two most important factors that define crop-livestock systems (McIntire *et al.*, 2002). In mapping poverty incidents in developing countries by farming systems, Thornton *et al.* (2002) modify the classification of livestock farming systems developed by Seré and Steinfeld (1996) who disaggregated the systems by agro-ecological conditions and population density. The livestock systems based on Thornton *et al.* (2002) are divided into; livestock only, rangeland based systems (LG: areas with minimum cropping), mixed rainfed systems (MR: mostly rainfed cropping combined with livestock), mixed irrigated systems (MI: where a significant portion of cropping uses irrigation and is interspersed with livestock).

Mixed rainfed farming systems (MR) are among the major production systems in developing regions. Mixed rainfed systems are further disaggregated by agro-ecological potential as defined by the length of growing period (LGP); i.e., mixed rainfed arid/semi-arid zone (MRA: with LGP <180), mixed rainfed sub-humid/ humid zone (MRH: with LGP <180), and mixed rainfed temperate/ highland zone (MRT: average temperature in growing season >5°C and <20°C, or a month or more with average >5°C). As shown in Fig. 1, if MRA, MRH and MRT are combined, mixed rainfed systems account

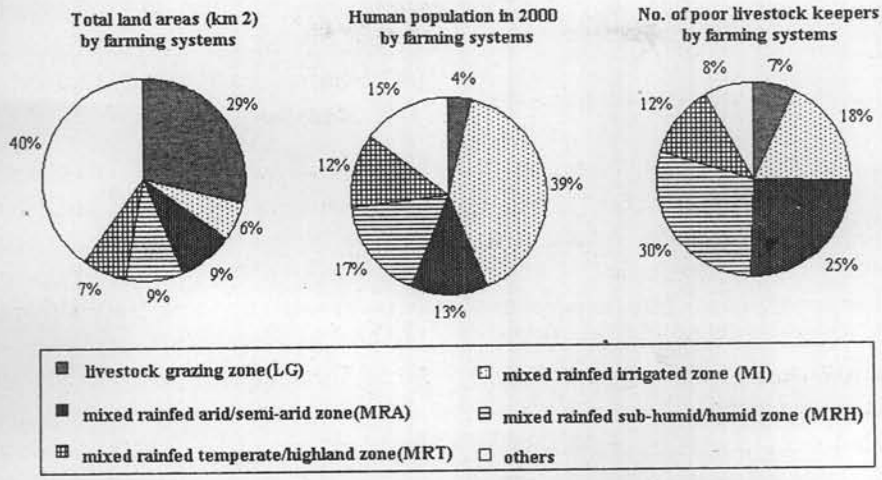

Fig. 1. Distributions of land areas, human population, and poor livestock keepers by livestock farming systems in developing countries (i.e. Thornton et al., 2002).

for 25% of the total land areas in developing countries, accommodating 42% of the population and 66% of the poor livestock keepers (Thornton *et al*., 2002). 37% of the total cattle and 36% of the sheep/goats in developing countries are also found in mixed rainfed systems (Steinfeld *et al*., 2006).

Variation: As already mentioned above, mixed rainfed farming systems are spread across the regions and are highly diverse even within subcontinents, as shown in Fig. 2, reflecting heterogeneities in agroclimates and population density. In general, the levels of crop-livestock interactions are low in arid, sparsely populated zones, while relatively high in cooler, more densely populated zones. In arid, sparsely populated zones, livestock graze open pastures and fallows are the principal means of maintaining fertility, giving few opportunities for crop-livestock interactions. In contrast, in cooler, more densely populated regions with few fallows, farmers must prepare feeds including harvesting crop residue, growing forage crops, and cutting native grasses; in turn, livestock produce manure to maintain soil fertility (McIntire *et al*., 1992).

Table 1 illustrates diversities in crop-livestock systems by continent, based on agroclimatic classifications and population density.

In Sub-Saharan Africa (SSA), mixed crop-livestock systems are the most important mechanisms for food production; 70% of the total SSA population depend on mixed crop-livestock systems (Thornton *et al*., 2002; Kristjanson and Thornton, 2004), and 80% of the cattle and sheep/goats in SSA are found in these systems (McIntire *et al*., 1992). Agroecological conditions greatly affect the geographical distribution of mixed systems in SSA. For example, in West Africa, integrated crop-livestock ownership is observed between zones neither too arid for crop cultivation nor

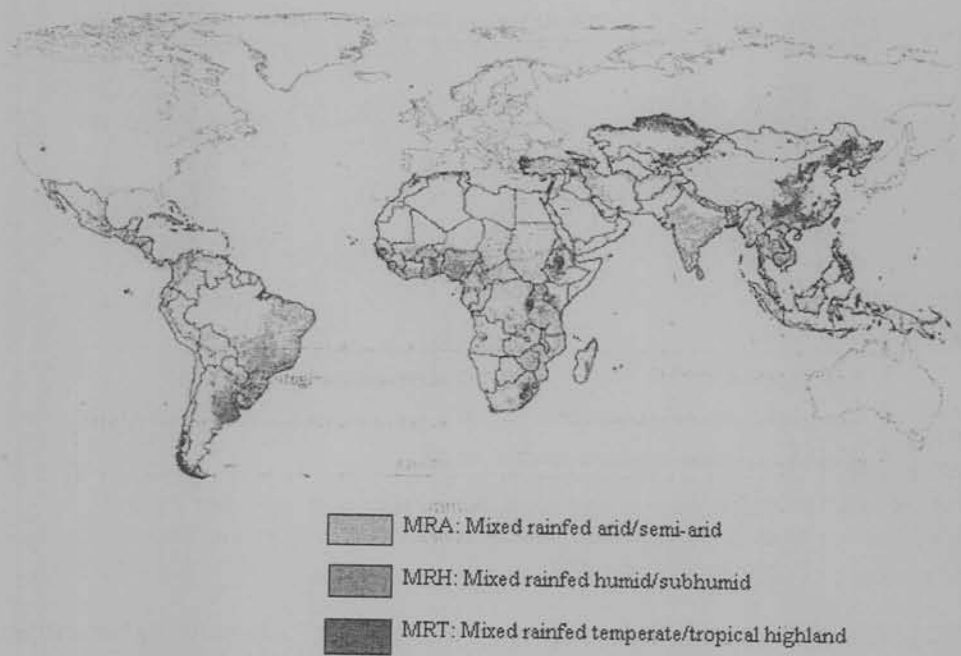

Fig. 2. Spatial distribution of mixed rainfed farming zones (Thornton et al., 2002).

too humid to allow diseases for livestock, such as tsetse and Trypanosomiasis (Powell and Williams, 1994; Hendrickx *et al.*, 2004; Manyong *et al.*, 2006). In East Africa, mixed farming systems are common in the highlands, and also in some semi-arid/sub-humid zones (Thornton *et al.*, 2002). Crop-livestock integration has already been established in cooler areas with higher population density, such as in highland zones in East Africa (Staal *et al.*, 2002; Place *et al.*, 2006; Tittonell *et al.*, 2005), where farmers employ manure for crop production, save crop residue for feed, and use animals for cultivation and transport. However, with the expected rapid population growth throughout mixed rainfed systems in SSA, agro-pastoralists are facing great challenges to cope with decreasing resource bases through better integration, especially in more arid zones with fragile soils.

Asian countries largely depend on mixed rainfed production systems. Both within Southeast and South Asia, 38% of the population and about 60% respectively of the poor livestock keepers live in the mixed rainfed farming zones. Within mixed rainfed farming zones, the main agro-ecological zones are sub-humid/humid in Southeast Asia, while those in South Asia are arid/semi-arid. Asian countries are characterized by extremely high population density in comparison to other regions. Probably due to high population pressure, crop and livestock integration has been well developed in small-scale agriculture, but land degradation has threatened the sustainability of the system. In Southeast

Table 1. Demographic situations by mixed rainfed farming zones (Thornton et al., 2002)

	Sub-Saharan Africa	Southeast Asia	South Asia	Latin America	West Asia North Africa
Total land area (%)	27	29	40	26	12
Arid/semi-arid (MRA)	14		28	5	9
Sub-humid/humid (MRH)	10	27	10	14	0
Temperate/highland (MRT)	3	2	2	7	3
Human population in 2000 (%)	70	38	38	51	40
Arid/semi-arid (MRA)	25		22	8	23
Sub-humid/humid (MRH)	30	37	15	24	1
Temperate/highland (MRT)	15	1	1	19	16
No. of poor livestock keepers (%)	78	63	61	68	57
Arid/semi-arid (MRA)	29	1	35	8	32
Sub-humid/humid (MRH)	32	60	24	36	2
Temperate/highland (MRT)	17	2	2	24	23
Population density in 2000 (per km^2)	68	139	289	49	107
Arid/semi-arid (MRA)	47		239	40	82
Sub-humid/humid (MRH)	78	146	457	43	0
Temperate/highland (MRT)	130	53	152	67	172

Asia deforestation is a major concern due to shifting cultivation and shortening of fallow, while in South Asia soil erosion is a serious problem (Thornton *et al.*, 2002; Devendra and Thomas, 2002a; 2002b; Paris, 2002). Better integration to ensure sustainable resource management will be urgently required as the systems must boost productivity to meet expected high demand for animal products following rapid income growth (Delgado *et al.*, 1999; Steinfeld, *et al.*, 2006). There are fewer case studies on crop-livestock integration in Asia, and this leads to a dearth of appropriate information.

Even fewer detailed case studies have been undertaken on the status of crop-livestock interaction in Latin America, West Asia and North Africa (WANA) regions, despite the fact that substantial portions of the population (51% in Latin America and 40% in WANA) including poor livestock keepers (68% of Latin America and 57% of WANA) depend on mixed rainfed farming systems (Thornton *et al.*, 2002; Thomson and Bahhady, 1995a).

Dynamics and challenges

Agricultural settings in mixed farming systems in developing countries are continuously evolving in response to certain driving forces (Pell, 1999; Pro-Poor Livestock Policy Initiatives, 2003). Below we briefly review some major driving forces, namely population growth and globalisation, and we predict their effects on the evolution of mixed farming systems.

Population growth: Thornton *et al.* (2002) forecast population growth in different farming systems in developing country regions by 2050 (Table 2) below.

Table 2. Population growth by mixed rainfed farming zones (Thornton et al., 2002)

	Sub-Saharan Africa	Southeast Asia	South Asia	Latin America	West Asia North Africa
Population density in 2050 (per km^2)	159	212	467	75	175
[times population density in 2000]	[2.3]	[1.5]	[1.6]	[1.5]	[1.6]
Arid/semi-arid (MRA)	106	0	397	55	132
	[2.3]	[0]	[1.7]	[1.4]	[1.6]
Sub-humid/humid (MRH)	192	222	707	70	0
	[2.5]	[1.5]	[1.5]	[1.6]	[0]
Temperate/highland (MRT)	290	81	253	100	283
	[2.2]	[1.5]	[1.7]	[1.5]	[1.7]

Estimates show that population density in 2050 will be highest in mixed rainfed systems in South Asia (467 persons/km^2) followed by Southeast Asia (212 persons/km^2) which already has a high population density. Mixed rainfed systems in Sub-Saharan Africa (from arid/semi-arid, sub-humid/humid, to temperate/highland zones) will see population density more than double (to 159 persons/km^2) by the year 2050.

This expected population growth will require an expansion in food production and increase in competition between crops and livestock. McIntire *et al.* (1992) claim that in the short-term, conflicts would occur over the use of high quality land, while in the long-term, population growth will intensify competition of crop and livestock enterprises for both land and labor. Rising population would also necessitate the expansion of cultivated areas, replacing pastures and thereby reducing the grazing area for animals. This indicates that unless farmers introduce intensive technologies such as high-yielding crop varieties or improved livestock breeds, it would be difficult to meet expected rising demand for animal products by the growing population (Delgado *et al.*, 1999; Pell, 1999; Steinfeld *et al.*, 2006).

Globalisation: McIntire *et al.* (1992) suggested that population growth would eventually ease labor constraints for manure and fodder production necessary to substitute for disappearing fallows and pastures. Whether intensification and integration will automatically happen is not certain, and this depends on whether rural farmers continue to specialize in farming activities and to allocate their labor to soil management activities in the era of globalisation.

Globalisation has led agro-pastoralists to diversify their livelihoods into non-farm/off-farm income generation activities. Globalisation and education promote lifestyle changes from subsistence to westernized consumption patterns. While returns from crop and livestock farming may highly fluctuate due to risks of crop failures and animal diseases, off-farm activities provide more reliable sources of income (for Africa: Reardon, 1997; Ellis, 1998; Ellis, 2000; Barret *et al.*, 2001; Bryceson, 2002; Tiffen, 2003; Ellis and Freeman, 2005; for Asia: Rigg, 2006; for Latin America: Escobar, 2001). Livelihood diversification and the increasing importance of off-farm income generating activities greatly affect crop-livestock intensification. Engagement in non-farm activities may encourage more crop-livestock integration by providing capital to invest in more intensive technologies, but it can also be discouraging if it constrains labor to be allocated to undertake such practices (Barret *et al.*, 2002).

Case studies from rural areas within Southern Africa provide an extreme example of negative impacts of de-agrarianisation on crop-livestock integration (Low, 1986; Ellis, 1998). Since the end of the 19th century, rural agro-pastoralists have been involved in the urban industrial economy in South Africa as migrant labor while their access to land was severely restricted in designated reserves for indigenous populations. By the mid-20th century, most adult males were absent from home, and the relative contribution of farming activities to livelihoods became increasingly marginal, as migrants rarely invested in crop-livestock farming (Low, 1986; Bundy, 1988). On the other hand, contrasting evidences have been observed in Eastern Africa and West Africa, that farmers with better access to high-return off-farm income generating activities are more likely to reinvest capital in improving crop-livestock technologies (Tiffen *et al.*, 1994; Tittonell *et al.*, 2005).

Probably these differences in reaction to involvement in off-farm activities are due to region-specific historical backgrounds, policies, and market/ infrastructure. Implications of livelihood diversification into off-farm income activities on crop-livestock integration require empirical investigation through comparative studies.

Degradational or conservationary pathways?

As mentioned above, mixed farming systems in developing countries have faced two main challenges: population growth and globalisation. To feed a growing population with more westernized consumption patterns, agro-pastoralists will need to accelerate the transformation of their production activities from subsistence to commercial farming and diversification into off-farm income activities. Much of the past expansion in commercial crop and livestock production has been managed by increased use of land at low inputs of capital and labor. As unoccupied land diminishes, increasing areas of natural vegetation have been transferred to arable areas with shorter fallow cycles. At the same time, competition between grazing and cultivating systems for available land has more than intensified. Hence, soil fertility is expected to decline unless some measures are taken to improve soil management.

Mortimore (1991) explained that "mixed farming systems are thus confronted with a choice between: (1) a degradational pathway - increasing the frequency of use without additional inputs, failing to replenish soil chemical properties or to conserve physical properties, and (2) a conservationary pathway - increasing inputs, especially of labor, to maintain or raise productivity per hectare. While animals are often blamed for degradation, they may, on the other hand, be an essential component of intensification, which, in turn, creates the economic conditions for conservationary land management."

In summary, the levels of crop-livestock interaction are primarily determined by agroclimatic conditions and population densities, while continuously evolving in response to driving forces. In future, population growth and globalisation may either encourage or discourage crop-livestock integration. It is therefore important to determine the extent to which crop-livestock integration offers solutions to the perceived crises discussed above and to identify the factors such as proper technologies and policies, infrastructure, and market opportunities, which will ensure "a conservationary pathway".

Multi-dimensional Aspects of Crop-livestock Integration

Effective research methodologies are needed to understand multi-dimensional aspects of crop-livestock integration; i.e., interactions between crop and livestock production; the circumstances promoting the evolution of mixed farming; and interactions between farming activities, off-farm activities and resource management. Though they are inherently interdisciplinary arguments, we tentatively categorize the methodologies into three: i.e. (1) system analysis approaches to model optimal scenarios on resource flows between system components, (2) empirical studies to identify meso-level factors affecting crop-livestock pathways, and (3) case studies to investigate effects of households' resource endowment and engagement in off-farm activities on the adoption of particular crop-livestock patterns.

While these approaches should be applicable elsewhere, so far relatively more case studies have been undertaken in Sub-Saharan Africa than in Asia, Latin America and WANA. This section reviews key concepts, methodologies and their applications in the recent literature on crop-livestock integration.

System analysis approach

Concept: System analysis approach in mixed crop-livestock systems attempts to analyze interactions of system components with a larger agro-ecosystem composed of non-agricultural systems, market systems and other biophysical conditions. Though the concept of system analysis is not new in the study of farming systems, the multiple roles of animals have been neglected until recently, due to their extreme complexities (Thomson and Bahhady, 1995a: Thorne, 1998; Pell, 1999; Devendra and Thomas, 2002a). System approach attempts to incorporate quantitative relations between crop and animal production, and to model optimal pathways of crop-livestock integration in terms of efficient nutrient cycling, in order to estimate a long-term impact of existing strategies on the sustainability of the system (Thornton and Herrero, 2001; Herrero *et al.*, 2007).

A conceptual framework for an integrated crop-livestock smallholder farm developed by Thorne (1998) is in Fig. 3. It illustrates the process of using inputs to produce outputs such as grain, meat, milk, crop, residues and manure at a farm level. Within this general framework, special attention is paid to the following interactions between crop and livestock components of the systems, i.e., organic resources and livestock, livestock and land, and livestock product utilization. The first two interactions generate a supply-side driving force in mixed farming systems, while the last factor is related to the farm household's consumption needs and other economic considerations, or the

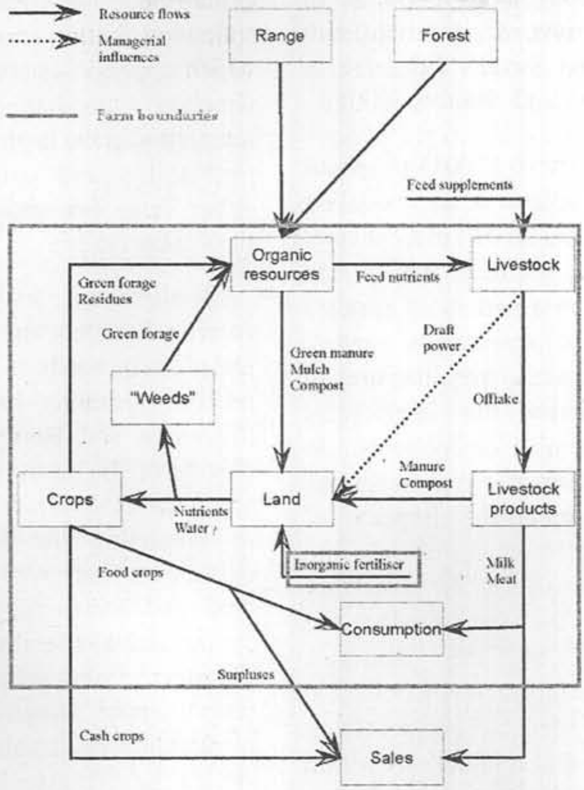

Fig. 3. Conceptual framework of crop-livestock integration by Thorne (1998).

demand-side driving force. Firstly, the interactions between organic resources and livestock revolve around the supply of nutrients and energy in feed, whose availability depends on grazing management intensity (i.e. free-ranged or stall-fed [zero-/semi-zero grazing]). Understanding these interactions of nutritional inputs facilitates prediction of animal performance. Secondly, an interaction between livestock and land through the management of stocking rates defines the productivity of grazing systems, while affecting cycling of nutrients from animals to crops wherever the two are associated, by providing manure, compost, and draught animal (Thornton and Herrero, 2001).

Methodology: As reviewed in the previous section, mixed crop-livestock systems in developing countries are facing tremendous socio-economic and environmental challenges due to population growth and globalisation. Modeling crop- livestock farm systems can help identify and quantify significant interactions that occur between the various components of smallholders' systems through simulation exercises of existing land use patterns or interventions. While a wide variety of separate crop and livestock models exists, the complicated nature of crop-livestock interactions in smallholder farming systems make it difficult to develop integrated models (McIntire *et al.*, 1992; Thornton and Herrero 2001).

Thornton and Herrero (2001) proposed that a conceptual framework for modeling crop-livestock systems should meet several requirements if the resulting models are to be used reliably in a variety of systems analysis and impact assessment studies. Among the requirements they list are: to describe and quantify the interactions between the system's components; to represent the farmer's management practices; to determine the impacts of management strategies on use of land and other resources; and to allow the possibility of studying both the medium-and the long-term effects of the strategies investigated. A set of logical methodological steps is required for adequately representing the components of, and transactions within and between, the systems to be modeled. Those steps include characterizing crop-livestock production systems, i.e. biophysical scales, management and interaction intensity, farm household objectives, temporal scales, and modeling the key components and processes.

Still, application of a modeling framework is quite challenging if dealing with all the interactions occurring in the system. One way to tackle the complexity in modeling is to develop relatively simple models based on either experimental or empirical farm types with site-specific parameters, by integrating information in a rational way to address specific research priorities. This approach is useful where the quantity or quality of data is insufficient (Thornton and Herrero, 2001). The following section reviews two case studies which applied system analysis methods to simulate impacts of crop-livestock integration at the farm level, on productivity, profitability and sustainability, based on either farm experimentation or empirical farm observation.

Application: In developing simple empirical models, the nature of the systems under study needs to be identified and the precise questions have to be addressed (Thornton and Herrero, 2001). Once the objects of the study set are identified, the approach is developed with the objective of predicting the long-term effects of existing or improved farming systems on crop and livestock productivity, nutrient cycles and availability, and farm income. In order to assess the potentials of particular crop-livestock integrations on productivity, profitability or sustainability, model farms should be compared with a comparable group of control farm types. Usually, model farms are devised to implement integration of crop and livestock production, while control farms are not.

An example of an experimental model farm approach is presented by Thomson and Bahhady (1995a; 1995b), based on the result of a six-year on-station experiment. Replicating local farming conditions prevalent in West Asia and North Africa at research stations, they devise experimental farm models with different levels of crop-livestock integration. In order to assess the potential long-term effects of better crop-livestock integration, i.e., better crop rotation practices and feed management, on crop yields and animal breeding productivity, three farm models are compared. These three farm models include the control farm with a minimal level of supplementary feed and natural pasture, the traditional farm with conventional fallow-rotation practices, and the integrated farm with better crop-rotation exercises with improved varieties for feed. Higher yields of feed and substantial improvements in sheep breeding performances subsequent to improvements in feeding level are observed when better integrated management practices are applied.

While Thompson and Bahhady (1995a; 1995b) use an on-station research approach to monitor farm performances in response to different crop rotation patterns, Shepherd and Soule (1998) employ existing mixed farm systems in the highlands of western Kenya as model farms to assess the long-term impact of existing soil management strategies on farm productivity, profitability, and sustainability. Three representative farm types are identified using participatory techniques to reflect differences in resource endowments and constraints faced by farmers, in terms of farm sizes and crop types, and quantity and quality of livestock. The long-term effects of different farm types with different resource endowments on soil management are evaluated by calculating material flows (including carbon, nitrogen, phosphorus), and monetary value, between system components and balances at farm levels. The low and medium resource endowment farms would have declining soil organic matter, low productivity and profitability. In contrast, the high resource endowment farms would have increasing soil organic matter, low soil nutrient losses and were productive and profitable.

These simulation models have advantages and some weakness. On-station research with the simulation of whole farm systems allows maximum biological and economic responses to the farm models under optimal conditions to be closely monitored. As Thomson and Bahhady acknowledge, the approach does not replicate treatments in space and it does not simulate the behavior and management of farms who face highly risky environments. Environmental factors, including agro- ecological, demographic and market conditions, significantly vary across regions and these local modifiers substantially affect localized crop-livestock evolution which does not necessarily follow optimal pathways. While it is not always easy to understand what is occurring in particular places (Herrero *et al.*, 2007), relative effects of the local modifiers on crop-livestock pathways should be empirically investigated.

Furthermore, while incorporating the basic elements of local farming systems as system components, i.e., crops, animals and natural pasture, the on-station model farm approach fails to account for the role of off-farm income activities in farms' decision-making of resource allocation to crop-livestock integration. In fact, Shepherd and Soule (1998) conclude from observing the existing farm types that low and medium resource endowment farms lacking capital resources, especially off-farm income, are constrained to adopt ecologically and economically sustainable soil management practices. But their initial farm classification, based on participatory techniques to reflect differences in resource endowments, resulted in poor categorization, as the low and medium farm types accounted for 90% of the total households in the study area (Tittonell *et al.*, 2005). Differences in degrees of engagement in off-farm income activities should be explicitly reflected in clustering farms with similar crop-livestock integration patterns, along with differences in resource endowment.

Effects of agro-ecological, demographic, market conditions on crop-livestock integration

Concept: Realities are often more complicated than simulated optimal pathways by the system analysis approach, because diverse and unpredictable factors complicate evolutional pathways of the crop-livestock systems (Williams *et al.*, 1999). The crop-livestock systems are neither closed nor static, but highly susceptible to changes brought about by surrounding systems, to which the sub-systems may respond in different ways. Crop-livestock integration may occur with intensification of existing technologies/ varieties induced by population growth and changes in the prices of land relative to labor (Boserup, 1965; Bourn and Wint, 1994), but it is more likely to occur with development/introduction of improved varieties and/or in response to market/ infrastructural development (McIntire *et al.*, 1992; Tiffen *et al.*, 1994; Williams *et al.*, 1999; Zaal and Oostendorp, 2002).

The determinants of particular crop-livestock intensification pathways (such as population pressure, policies, market and infrastructure development) merit empirical investigation at meso-levels, through cross-section analyzes. This sub-section reviews empirical studies which investigate the effects of agro-ecological, demographic and market conditions on crop-livestock integration, using variables reflecting both location-specific proxies and village/ household characteristics. Some studies estimate factors influencing the adoption of new crop/ livestock varieties and integrated technologies (Staal *et al.*, 2002; Kristjanson *et al.*, 2002, 2005). Others attempt to invent indicators to effectively capture multi- dimensional aspects of crop-livestock integration and then examine factors affecting them (Manyong *et al.*, 2006).

Methodology and application I: Technology adoption: As already discussed, mixed crop-livestock systems at a given place and time are largely defined by agro-ecological potentials and population density. On the other hand, crop-livestock integration is a dynamic process involving farms' decision making process to adopt more intensive technologies in response to challenges posed to their systems by population growth and globalisation (McIntire *et al.*, 1992; Pender *et al.*, 2004). Technology adoption can be a proxy to some dimensions of crop-livestock integration. Furthermore, crop-livestock integration often shows certain spatial patterns, with some areas observing more farms adopting new technologies than others. In empirically estimating factors driving technology adoption and determining their spatial patterns, many studies assume that whether a farm adopts a particular technology or not is a function of location specific factors, such as agro- climate, demographic, and market conditions, and household-specific factors. In efficiently capturing the dimension of locational factors, more recent studies incorporate GIS (geographical information system)-derived measures into their econometric models. Below, empirical studies of technology adoption by

Table 3. Model summaries for Staal et al. (2002) and Kristjanson et al. (2002)

Authors	Staal *et al.*, 2002	E	R	Kristjanson *et al.*, 2002	E	R
Study area	Central and Western Kenya, East Africa			Dry savannahs Nigeria, West Africa		
Farm activities	Mixed rainfed			Mixed rainfed		
Crop types	Maize and napier fodder			Sorghum, millet, cowpea		
Model	Logit			Tobit		
Dependent variable	Keeping dairy cattle planting of fodder use of concentrate feed			% of village cropped area to improved double-purpose cowpea		
Independent variables	Agri potential [GIS]	+	+	Population and market [GIS]	+	+
	Population density [GIS]	+	+	Livestock density [village]	+	+
	Market distance [GIS]	-	-	Cowpea importance [village]	+	-
	Household [household]	+	+	Extension service [village]	+	-
				Price dummy [village]	+	+

Note: E expected, R realised, + positive, - negative.

smallholding agro-pastoralists (Staal *et al.*, 2002; Kristjanson *et al.*, 2002) are reviewed, and major characteristics of their models are summarized in Table 3.

Staal *et al.* (2002), investigate the effects of locational factors on technology adoptions in mixed smallholder farming systems in central and western Kenya. The three technologies considered as proxies of crop-livestock integration include keeping of dairy cattle, planting of specialized fodder, and use of concentrate feed. The study is especially interested in the effects of market and infrastructure access among locational factors on technology adoption, because smallholding dairy systems have been critically dependent on infrastructure, access to roads and milk collection centers. A set of GIS-derived measures of market access, agro-climate and demographic conditions, are included as explanatory variables along with household characteristic variables in a standard household model of technology uptake. As expected, GIS-derived measures of better market access (less distance), agricultural potentials, and population pressure are strongly associated with technology adoption, along with household capital asset variables, such as farming experience and level of education of the household head.

Kristjanson *et al.* (2002), on the other hand, examine the ability of village-level factors to potentially influence spatial patterns in crop-livestock evolution pathways in West Africa. Grain and leaves of genetically improved cowpea varieties in dry savannahs are highly nutritive food for both human beings and livestock, thus the adoption of these double-purpose cowpea varieties can be a proxy of crop-livestock integration. Locational factors, such as population density, market access, and frequency of visits by village extension officers, are expected to positively influence adoption by making better integration necessary, profitable, and accessible. Therefore, the study estimates the intensity of adoption at village level, expressed as the percentage of village area cropped to improved cowpea varieties, as a function of locational variables derived from GIS and village-level interviews using a tobit model. GIS-derived variable captured socio-economic domains, reflecting the interaction between human population density and market infrastructure. The results show that, as expected, the intensity of adoption was higher in the more densely populated, better-market-access domains. On the other hand, the frequency of visits by an extension agent turned out to have a negative effect, requiring further investigation for better targeting strategies.

These empirical studies reveal significant effects of locational factors, i.e., agro-ecological, demographic, and market conditions, on farmer decisions in technology adoption which contribute to crop-livestock integration. They also present potentials of utilizing GIS technologies in identifying target areas.

Methodology and application II: Effective dimensionality: Most recent literatures deal with selected technologies as proxies of crop-livestock integration. The technologies in question may not only vary across locations but also across studies, meaning that we may have to deal with several different measurement parameters; crop-livestock integration is a universal concept for such a multi-dimensional phenomenon. Using manure, animal traction, crop residue, and agricultural by-products as feed within the same farm enterprise are important indicators of multi-dimensionality in the integration of crop and livestock systems. Manyong *et al*. (2006) propose a new framework for measuring the multiple dimensionality of crop-livestock integration (CLI), in order to facilitate a more universal understanding of the phenomenon, and to enable comparison of evidence across locations by combining the various indicators to construct farm-specific indices for intensification in CLI.

Principal component analysis was employed to derive a new CLI index to reflect the most common single features from the original indicators. Principal component analysis is a multivariate tool that is used to summarize information contained in a set of original multivariate data to arrive at a fewer number of new variables (Everitt and Dunn, 2001). Manyong *et al*. (2006) apply this method to empirical household data in mixed farming systems across savanna regions in Nigeria. The original variables are five CLI indicators at household-level, including quantity of manure used, frequency of animal traction, quantity of crop residues, and quantity of agricultural by-products, and use of chemical fertilizers. A principal component analysis of these five CLI indicators results in three principal components. Manyong *et al*., 2006 invent a CLI index using a linear recombination of the three principal components.

This CLI index could be used as a single dependent variable in a regression analysis to represent intensity in CLI, since it retains the information contained in the original five CLI indicators. In dry savanna regions in West Africa, CLI initially increases along a north-south axis and then declines, indicating that the latitude probably identifies the boundary below which disease challenge constrains traditional livestock production and CLI. Manyong *et al.*, 2006 also estimate parameters of factors affecting CLI, including variables reflecting household resources, agro-ecological conditions, and GIS-derived village-level market and institutional factors. Agro-ecological factors, market access, and institutional factors are found to have most impact on the probability of high intensities of CLI.

The typology of crop-livestock integration pathways has long been challenging. Earlier attempts tried to disaggregate multi-dimensional features of crop-livestock integration and to classify farming systems into zones with particular features (Mortimore, 1991). The new framework, on the other hand, derives farm-specific intensification indices by summarizing and reducing the multiple dimensionality of crop-livestock integration. Investigation of the relations between such aggregated farm-specific CLI index and GIS-derived locational factors as well as questionnaire-based household/community characteristics can be an effective way of identifying driving forces of crop-livestock integration.

Effects of households' resource endowment and off-farm activities on crop-livestock integration

Concept: As previously discussed, major factors determining spatial patterns of crop-livestock integration are agro-ecological, demographic, and market conditions. On the other hand, as system analysts have acknowledged, even within a small area, degrees of crop-livestock integration and adoption of resource management practices have been highly heterogeneous among farmers with different resource endowments and involvement in off-farm income activities (Shepherd and Soule, 1998). In-depth case studies are necessary to gain critical insights into crop-livestock integration from a perspective of household livelihoods strategies. Such studies are also necessary to investigate the role of human capital as well as the impacts of off-farm income activities on human choices and responsiveness to economic and ecological challenges.

Farms may choose portfolios of crop and livestock to maximize utility or income under their resource constraints, and to allocate land, labor, and capital accordingly. Different sets of crop-livestock types, i.e. indigenous or exotic, subsistence or commercial, have different levels of interactions between components, economic returns and input use (Kristjanson and Thornton, 2004). Facing similar agro-ecological, demographic, and market conditions, farms better endowed with assets and off-farm income might adopt higher-return crop-livestock portfolios. Thus, higher returns would encourage farms to invest in more integrated management to improve sustainability of resource bases within the farm. However, empirical studies on these subjects have been relatively few (Tittonell *et al.*, 2005; Iiyama *et al.*, 2007).

Methodology and application I: Categorizing farm types: Observation of heterogeneous processes of soil degradation at region and/or at farm levels in mixed smallholder systems indicates that causes of variability in resource and soil management are not only biophysical, but also socio-economic. In order to analyze the impact of heterogeneous land use patterns on nutrient flows and to identify targeting strategies and technologies, Tittonell *et al.* (2005) proposed the identification of representative farm types. Using household/farm data from highly populated highland zones in western Kenya, Tittonell *et al.*, 2005 initially attempted to classify farms based solely on resource endowment (high [HRE], middle[MRE], or low[LRE] endowment of land, livestock, or other assets), but this led to poor discrimination of resource allocation patterns. They therefore added information on production goals (e.g. self-subsistence, market orientation), the main types of constraints faced (land, labor, capital), position in the farm development cycle (age and sex of household head, family size), and main source of income (salary, cash crop, farm produces, informal labor). As a result, five representative farm types were identified to reflect the heterogeneity in soil fertility management and nutrient resource flows.

Farm type 1 [(a) HRE, (b) self-consumption, (c) land, (d) small family, (e) salary dependent] was the wealthiest, followed by farm type 2 [(a) HRE, (b) market-oriented, (c) -, (d)old head, large family, (e) cash crops], while farm type 5 was the poorest [(a) LRE, (b) self-subsistence, (c) land, capital, labor, (d) often women-headed, (e) selling labor]. Farm types 3 and 4 were intermediate in wealth and in size. Both farm types 1 and 5 relied on off-farm earnings and sold the least farm produce to the market, but the magnitude of their cash, labor and nutrient flows was contrasting. A consistent trend of decreasing input use from farm types 1-5 was generally observed. These farm types affected the pattern of resource flow at farm scale, especially of use of manure.

Clustering farm households into farm types with similar resource management patterns facilitate in-depth investigation of crop-livestock integration, while requiring researchers to take various farm characteristics into consideration.

Methodology and application II: Crop-livestock diversification patterns: Resource management and crop-livestock activities are closely associated. Investments in resource management are not made in isolation with the preceding investment in crop and livestock activities. Farmers who have invested in valuable perennials (e.g. fruits) may find adoption of soil conservation practices more attractive than in the absence of such prior investments (Barrett *et al.*, 2002). Improved breeds of animals are more likely to be stall-fed within farms rather than grazed on commonages, and more integrated with crop production (Staal *et al.*, 2002; Bationo *et al.*, 2004). Examining households' patterns of adopting distinctive crop-livestock activities can be an alternative way to identify farm types based on degrees of integration. Iiyama *et al.* (2007) propose a concept crop-livestock diversification (CLD) patterns, defined as particular combinations of crops and animals, and applied that concept to analyzing inter-household heterogeneity in CLD patterns observed in a Rift Valley community, western Kenya.

Principal component analysis was used to derive the dominant CLD patterns which reflect complementarities between crop and livestock types. In the case of western Kenya, there were initially ten variables representing relative engagement by farm households in particular crop-livestock activities, i.e. crop types (share of areas cropped to drought-resistant, staple, fruits, commercial crops as well as the total area used) and animal types (share of animals held in exotic cattle, dairy goats, indigenous cattle, indigenous sheep/goats as well as the total livestock owned). Principal component analysis yielded five principal components which can be interpreted as five distinctive CLD patterns adopted by households: (i) maize + indigenous cattle, (ii) improved cattle + fruits, (iii) extensive crop production, (iv) sheep and goats, and (v) dairy goats.

Among the five CLD patterns, the CLD of [improved cattle + fruits] was identified as a sustainable crop-livestock integration pathway, more associated with higher farm and off-farm income and better utilization of organic manure. Conversely, households that grew staple crops with or without indigenous animals were found to apply less manure. Thus, characteristics of households adopting the CLD pattern of [improved cattle + fruits] were examined. Education, participation in farmers' groups, access to the training center, and family size, were key factors affecting the adoption of this CLD pattern. This method can reveal combinations which ensure sustainable crop-livestock integration pathways, and others which have economic-environment trade-offs.

Conclusion

This paper reviews the current status of and challenges to mixed farming systems in developing countries. Mixed rainfed farming systems are highly diverse across the regions, reflecting heterogeneities in agroclimates and population density. In Sub-Saharan Africa, mixed crop-livestock systems are facing great challenges in coping with decreasing and degraded resource bases as the systems are projected to experience increased population growth in the first half of the 21st century. Asian countries are characterized by extremely high population density and well-developed crop-livestock integration in small-scale agriculture, yet land degradation has threatened the sustainability of the systems. On the other hand, less information has been available on the status of crop-livestock interaction in Latin America, West Asia and North Africa (WANA) regions, despite their importance for poor livestock keepers.

In order to feed growing populations, agro-pastoralists are urged to accelerate transformation of their productive activities from subsistence to commercial farming and diversification into off-farm income generating activities. Unless more intensive technologies are adopted, expansions of productive activities on limited resources will lead to serious soil degradation. It is thus important to determine the extent to which crop-livestock integration offers solutions to perceived crises and to ensure provisions of proper technologies, policies, infrastructure, and market opportunities.

The paper also reviews major concepts and methodologies that are recently employed to investigate multi-dimensional aspects of crop-livestock integration. System analysis approach has shown potentials that crop-livestock models can be used for scenario generation and impact assessment. On the other hand, realities are often more complicated than simulated optimal pathways, because diverse and unpredictable factors often complicate evolutional pathways of the crop-livestock systems. Some studies empirically investigated and confirmed the effects of agro-ecological, demographic and market conditions on determining crop-livestock integration and their spatial patterns. Others conducted in-depth case studies on crop-livestock integration from a perspective of households' livelihood strategies, especially on the roles of human capitals as well as the impacts of off-farm income activities on human choices.

As this review paper has indicated, rising population pressure and expanding economic activities would accelerate depletion of resources and aggravate poverty in mixed rainfed systems, unless rural populations intensified current resource use practices. Furthermore, global warming will make agro-pastoralists in arid/semi-arid zones more vulnerable than ever to climatic changes. Therefore, there is little time and resources to be wasted. Those concerned with the potential contribution of crop-livestock integration to sustainable development should galvanize efforts in mobilizing and consolidating knowledge and expertise.

To mobilize experiences on crop-livestock integration, more cross-sectional studies as well as in-depth case studies are necessary. For comparative studies, more researchers are eager to experiment newly developed crop-livestock models to situations in Sub-Saharan Africa. On the other hand, little information is yet available on crop-livestock integration in Asia, Latin America and WANA. In order to promote comparative studies, Herrero *et al.* (2007) developed a programme called IMPACT (integrated modeling platform for animal-crop systems), which aims at reducing high costs and time associated with collecting information and developing a data base to permit a systematic comparative analysis of a range of problems facing smallholders. In-depth case studies would contribute to improving models for dissemination, by using models and integrating participatory methods that include stakeholders at all stages of model development and most importantly, at the later stages for strategy selection and dissemination.

Collaboration among researchers is necessary to consolidate expertise both in the natural and social sciences and to translate findings into policies. Various branches of the natural sciences, e.g., crop, animal, and soil sciences, are necessary to develop new cost effective technologies aimed at improving livelihoods, to assess physical conditions, to estimate maximum nutrient recycling potentials, and to determine appropriate sets of technologies for particular locations. On the other hand, the fundamental causes of resource depletion are socio-economic, including (a) extensive but low-return farming technologies, and (b) lack of alternative livelihood options to the poor. Therefore, crop-livestock integration could be achieved if they can generate more profits on limited land and provide rural smallholders with improved livelihood options. Therefore, poverty reduction and environmental conservation policies need to be developed in order to link improved livelihood options, including crop-livestock integration, with effective resource management.

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