

# Integrated crop–livestock simulation models for scenario analysis and impact assessment

P.K. Thornton<sup>a,\*</sup>, M. Herrero<sup>a,b</sup>

<sup>a</sup>*International Livestock Research Institute (ILRI), PO Box 30709, Nairobi, Kenya*

<sup>b</sup>*Institute of Ecology and Resource Management (IERM), University of Edinburgh, West Mains Road,  
Edinburgh EH9 3JG, UK*

Accepted 30 March 2001

---

## Abstract

Despite the fact that many smallholder farming systems in developing countries revolve around the interactions of crop and livestock enterprises, the modelling of these systems using combinations of detailed crop and livestock models is comparatively under-developed. A wide variety of separate crop and livestock models exists, but the nature of crop–livestock interactions, and their importance in smallholder farming systems, makes their integration difficult. Even where there is adequate understanding of the biophysical processes involved, integrated crop–livestock models may be constrained by lack of reliable data for calibration and validation. The construction from scratch of simulation models that meet the needs of one particular case is generally too costly to countenance. As for all modelling activity, the most efficient way to proceed depends on the nature of the systems under study and the precise questions that have to be addressed. We outline a framework for the integration of detailed biophysical crop and livestock simulation models. We highlight the need for minimum calibration and validation data sets, and conclude by listing various research problems that need attention. The application of robust and trustworthy crop–livestock models is critical for furthering the research agenda associated with animal agriculture in the tropics and sub-tropics. © 2001 Elsevier Science Ltd. All rights reserved.

**Keywords:** Crop–livestock interactions; Model; Simulation; Economic surplus; Decision-support systems

---

---

\* Corresponding author.

*E-mail address:* p.thornton@cgiar.org (P.K. Thornton).

## **1. Introduction**

Mixed crop–livestock systems constitute the backbone of much agriculture in the tropics. The demand for livestock products is forecast to skyrocket well into the next century (Delgado et al., 1999). How producers are going to respond to this increased demand is the subject of considerable ongoing study, particularly in terms of the intensification pathways that different production systems may follow (e.g. McDermott et al., 1999). There is little doubt, however, that especially in sub-Saharan Africa, increasing integration of crops and livestock is going to occur over at least the next 30 years.

Given their prevalence in the tropics, the general lack of knowledge concerning what actually goes on in these complex smallholder mixed systems is, in some respects, hard to comprehend. A similar sentiment has been expressed with respect to the economics of animal disease relatively recently (McInerney, 1996). For animal health economics, it may well be a case of applying ‘old economics’ to the ‘new problem’ of livestock disease, although there are various plausible reasons to explain the fact that this area is significantly under-researched (Rushton et al., 1999). On the other hand, in terms of the study of crop–livestock systems and their interactions, it is not simply a case of ‘new problem, old solution’. Modelling realistically offers the only way of identifying and quantifying the subtle but often highly significant interactions that occur between the various components of smallholders’ systems. Without this, there are clear limits to what can reliably be said about the wider impacts of intervention and change on these types of production systems.

In this paper, we outline some issues related to the development of integrated crop–livestock simulation models, and we discuss potential uses of such models in studying mixed crop–livestock farming systems in the tropics. We start from a consideration of the complexity of crop–livestock systems, and highlight components, constraints and problems, and the major interactions, particularly with regard to management issues. This is followed by a discussion of a conceptual modelling framework, in relation to precision, scales, and integration of temporal and spatial aspects, and then we discuss some key aspects concerning the integration of existing crop and livestock simulation models to describe these systems. We discuss how such models can be used for scenario analysis and impact assessment. We outline how these tools can be applied for dissemination and promoting adoption of interventions and management packages for smallholder farmers. The paper concludes with a listing of various areas where there are substantial research needs in the modelling of crop–livestock systems.

## **2. Crop–livestock systems**

Globally, the next 20 years will see a massive increase in demand for food of animal origin, with virtually all the increased demand coming from the developing countries (Delgado et al., 1999). There are clearly vast opportunities for livestock producers in the tropics to meet this rising demand. There are also profound

implications for evolving livestock production systems, for the environment and for smallholders' welfare as a result. The challenges and opportunities depend very much on the region and systems under consideration. Grazing systems, for example, currently utilize almost a quarter of the world's land area and produce one tenth of its meat requirements. Traditional grazing areas are coming under increasing pressure largely because of human population growth. It is doubtful if there is much scope for greatly increased production from these areas (Von Kaufmann, 1999).

Mixed crop–livestock systems provide over 50% of the world's meat and over 90% of its milk and are the most common form of livestock operation in developing countries. In addition, mixed systems include some 70% of the poor livestock keepers. Fig. 1 shows the economically important livestock systems in developing regions [Von Kaufmann, 1999 using data from Seré and Steinfeld (1996) and Delgado et al. (1999)]. It is noteworthy that the most economically important livestock systems in Asia, Latin America and West Asia-North Africa are mixed systems. As population density increases and less land becomes available, there is a general trend for crop and livestock activities to integrate. Livestock, and particularly ruminants, will continue to play key roles in providing draught power, manure to maintain soil fertility, animal food products, and opportunities for increased income generation. It seems likely that in much of the developing world, there will be an emphasis on milk production in crop–livestock systems involving ruminants, largely because of milk's ability to generate daily income for the smallholder household. 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.

Increasing the linkage between crop and livestock production is an effective means by which plant nutrients can be rapidly recycled within and between farms. On the

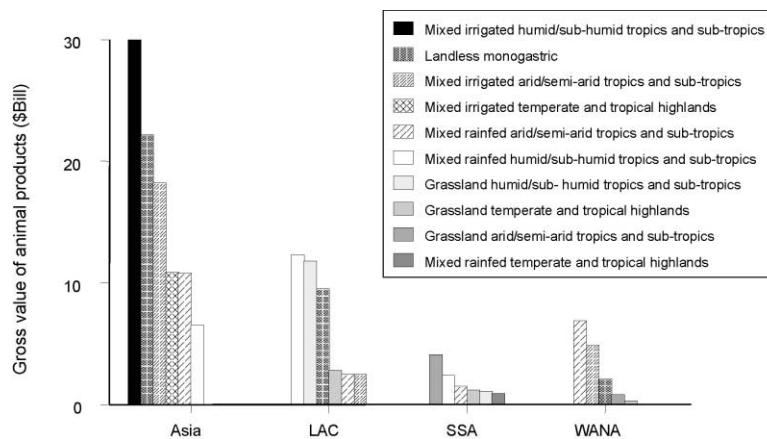


Fig. 1. Economically important livestock systems in Asia, Latin America and the Caribbean (LAC) and West Asia-North Africa (WANA). The gross value of animal products includes beef and veal, buffalo meat, sheep and goat meat, total milk production, pig meat, poultry meat and eggs. Source: Von Kaufmann (1999) using data from Seré and Steinfeld (1996) and Delgado et al. (1999).

other hand, the factors driving intensification often lead to the expansion of cropped areas and more intensive cropping practices at the expense of grazing land. In the face of declining grazing land the potential of arable land to provide fodder throughout the year must be enhanced, if the important role of livestock within the farm system for household welfare is to be maintained or developed. A generalized mixed farm is shown schematically in Fig. 2 (based on Thorne, 1998), illustrating the process of using inputs to produce outputs such as grain, meat, milk, crop residues and manure.

### 2.1. Crop–livestock component interactions

Within the general framework of Fig. 2, there are several key interactions between the various crop and livestock components of the system (McIntire et al., 1992; this section follows Thorne, 1998 closely).

#### 2.1.1. Organic resources and livestock

The interactions between organic resources and livestock revolve mostly around the supply of nutrients and energy in feed, hence the need to use models capable of predicting animal performance from given plant and animal characteristics. A substantial number of these models can be found in the literature and their use depends on research objectives, data availability and precision required (see reviews by Illius and Allen, 1994 and Herrero et al., 1998). These range from relatively simple requirements systems such as those proposed by SCA (1990), Alderman and Cottrill

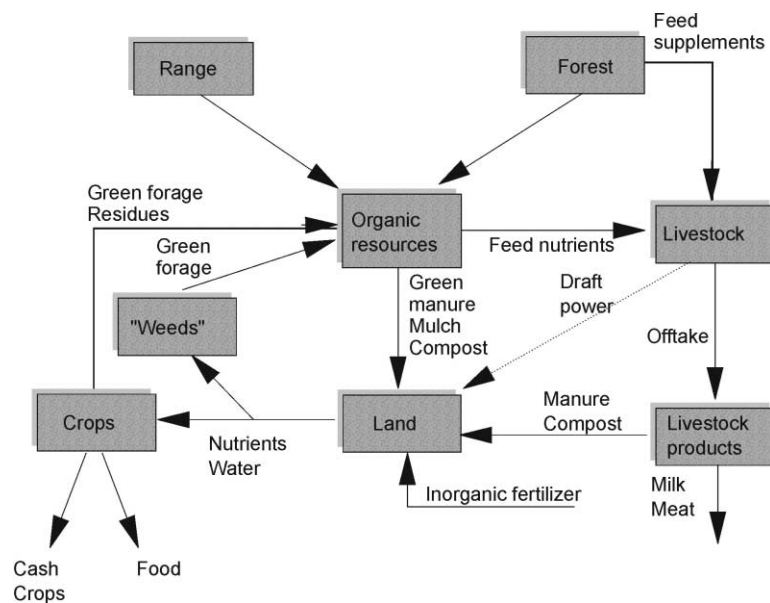


Fig. 2. Schematic representation of a farming system based on the integration of crops and livestock. Source: based on Thorne (1998), adapted by G. Hoogenboom (personal communication).

(1993) and NRC (1996) to models that represent the flow of feed through the gastrointestinal tract of ruminants (Baldwin et al., 1987; Illius and Gordon, 1991; Sniffen et al., 1992).

These nutritional inputs can be managed indirectly, in a grazing or browsing situation, and directly, with feed offered to stall-fed livestock. In most grazing situations, animals have considerable freedom in choosing what to eat, although the manager can control length of access time. Stall-feeding is common in mixed farming systems because it allows farmers to exert more control over the valuable manure outputs of their animals. It also reduces the possibility of damage to crops that may be caused by free-ranging livestock (Thorne, 1998). In some systems, stall-fed livestock will be grazed as well, often at a particular time of year when seasonal factors make this desirable.

#### *2.1.2. Livestock and land*

An obvious interaction between livestock and land is through the management of stocking rates, which plays a large part in defining the productivity of grazing systems (see, for a review, Humphreys, 1991). Modelling grazing systems has received substantial attention and several examples of integrated models varying widely in degree of complexity can be found in the literature (e.g. Hanson et al., 1988; Blackburn and Kothmann, 1989; Thornley and Verberne, 1989; Stuth et al., 1990; Stafford-Smith, 1992; Donnelly et al., 1997; Loewer, 1998). (See Stuth and Lyons, 1993 and Herrero et al., 1998 for a more comprehensive review of grazing systems models and modelling approaches.)

The livestock–land interaction also includes the production of manure and compost, and the provision of draught animal power. Livestock play a key role in the cycling of nutrients to crops, wherever the two are associated (Powell et al., 1995). To date, few attempts have been made to derive integrated models in which dynamic processes in livestock are linked with dynamic processes in soils in the tropics. Examples from temperate regions include those of Parton et al. (1987, 1994) and Thornley and Verberne (1989).

In general, draught animals are used as tools in the management of the soil through tillage operations, although their role in support of crop processing and marketing activities is important in some situations. Farmers' perceptions of draught animals in mixed farming systems are often ambiguous (Thorne, 1998). Access to them is seen as essential when land preparation must be carried out. At other times, draught animals may be managed on the basis of maintenance. Some of these aspects have been incorporated in the model of Van der Lee et al. (1993).

#### *2.1.3. Livestock product utilization*

The availability of organic resources and constraints to their utilization generate a supply-side driving force in mixed farming systems. The demand-side driving force will usually be the farm household's consumption needs and other economic considerations. Various economic models have been constructed to examine the behaviour of farmers in pursuit of household food security and income generation objectives. These are often based on a simplified treatment of the biophysical

processes occurring in the production system, thus precluding an evaluation of the consequences of interactions between processes in different components of mixed farming systems. Such models are thus not well-suited to a detailed analysis of the impacts of component interventions at the system level. On the other hand, there is the problem of how to take the outputs from detailed biophysical models and place them in an appropriate farm household context (Dent and Thornton, 1988). Clearly, biological modelling activities must be integrated with an appreciation of farmers' objectives in the systems that are being targeted (Thorne, 1998).

### **3. Towards a conceptual modelling framework**

A conceptual framework for modelling crop–livestock systems should meet various requirements if the resulting models are to be used reliably in a variety of systems analysis and impact assessment studies. Crop–livestock systems models should be able to do the following, at a minimum:

1. Describe and quantify the interactions between the system's components.
2. Represent the farmer's management practices.
3. Determine the impacts of management strategies on use of land and other resources.
4. Quantify nutrient balances at the whole-system level.
5. Quantify the variability associated with different weather conditions on system performance.
6. Provide insight into the trade-offs (economic, environmental and social) involved in using different farm resources.
7. Allow the possibility of studying both the medium- and the long-term effects of the strategies investigated.
8. Translate model outcomes into operational support for seasonal farm management. For example, in the case of livestock they should be able to provide herd, grassland and feeding management strategies, while for crops issues such as planting density and manure/fertilizer applications may be of paramount importance.
9. Use minimum data sets for parameterization, validation and general use, that can be assembled relatively easily.
10. Integrate data from different levels of aggregation.

It is clear that there is a range of models that have dealt successfully with some of the issues outlined above (Stoorvogel et al., 1995; Hansen, 1996; Shepherd and Soule, 1998; Herrero et al., 1999a). However, there has not been a single unifying framework that has dealt satisfactorily with all these requirements simultaneously. Such a framework should be based on a system that permits the integration of a range of models varying in level of aggregation and data requirements. Depending on data availability in any situation and the objective of the study, these could be linked through standard data communication protocols.

To achieve such models, a set of logical methodological steps is required. The following are some issues that need to be addressed for adequately representing the components of, and transactions within and between, the systems to be modelled.

### 3.1. *Characterizing crop–livestock production systems*

This is the first, and one of the most important, steps for designing models for studying crop–livestock systems and their interactions. This step should help to define the limits, problems and constraints of the system (ecological, biological, economic and social) and should ultimately help in defining the type of system and its behaviour. It should answer the following questions:

1. Do we know enough about the systems we are hoping to model?
2. Do we have enough data for representing them properly?
3. Are we prepared to generate or collate any missing data for describing them adequately?

If the answer to any of these is no, then it is very unlikely that modelling is an appropriate tool for that particular systems analysis and impact assessment study. Characterization studies should take into account the following:

*Biophysical scales:* the question of scales, and the scaling up and down of data, models, and model outputs, are frequently discussed aspects of systems analysis and ecoregional research activities. The use of a particular scale is determined by the objective of the analysis. An example of different biophysical scales and their different levels of data and analysis aggregation is shown in Fig. 3, from Li Pun et al. (1999). Each hierarchical level has its own set of data collection mechanisms as demonstrated by Stoorvogel et al. (1995). For example, at the household and community levels, data are usually collected by direct interviews with the farmers and other members of the household (surveys), while reliance on secondary data is necessary at higher levels of aggregation and some degree of experimentation is required at lower levels. Information flows between hierarchical levels need not be mutually exclusive, although it is in principle easier to aggregate and inherit data and concepts as the hierarchical level becomes more aggregated, rather than to decompose data to lower levels. Nevertheless, for an appropriate understanding of farm household systems and their behaviour it is necessary to put them into their agro-ecological and community contexts. Therefore, strategic information from higher hierarchical levels is necessary to provide a more complete description of the system under study.

*Management and interaction intensity:* at the household level, the first stage in characterizing a system should be to define its components and the main interactions between them. This has been done systematically in some studies through the implementation of farming systems description and monitoring software (Jansen and Schipper, 1995; De Jager et al., 1998; Solano et al., 2000a). In cases where this is not done satisfactorily, the information obtained does not then present a clear picture of how the system works. The main reason for this is an

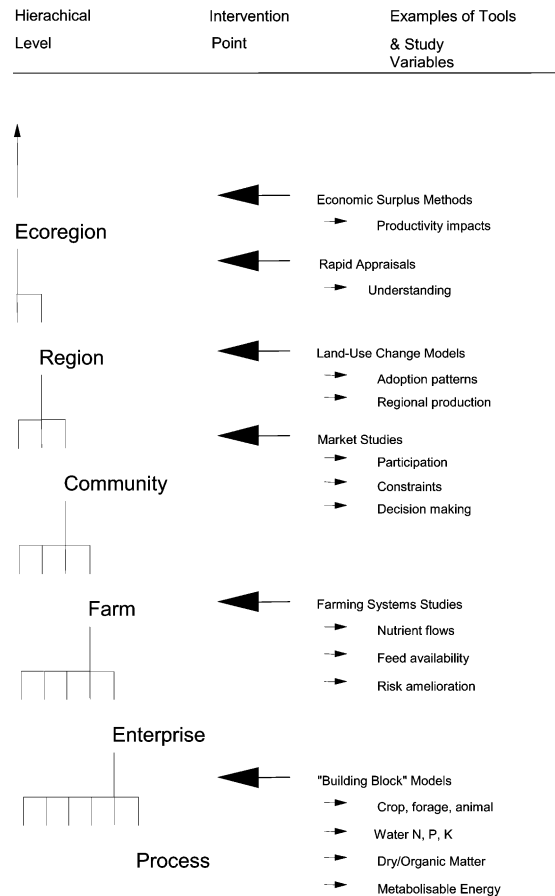


Fig. 3. Some tools and study variables for the analysis of agricultural systems at different hierarchical levels. Source: Li-Pun et al. (1999).

incomplete description of the management intensity and the interaction intensity within the system. Both reflect the managerial capacity of the farm household, but management intensity deals mostly with the level and frequency of management interventions *within* each of the system's components, while interaction intensity is determined by the level and dynamism of the interactions *between* the components. These two factors help define the realism with which a model can operate and partly determine the predictability of the behaviour of the system.

*Farm household objectives:* as noted above, characterization of crop–livestock systems has traditionally focused on their physical components and their management without taking into account the objectives and reasons driving the farm household to manage their system in a particular way. This omission is believed by many authors to be one reason for lack of adoption of technology in crop and livestock systems (Dent and Thornton, 1988; Chambers et al., 1993; Dent, 1995;



Ferreira, 1997). The subject has been difficult to study and has encouraged a greater input from the social sciences. Recent studies such as those of Fairweather and Keating (1994), McGregor et al. (1995), Ferreira (1997) and Solano et al. (2000a, 2000b) have helped bridge some of the methodological gaps for taking into account these aspects in systems analysis and technological dissemination. For example, the work of Solano et al. (2000a, 2000b) included participatory methods for data collection and used analytical methodologies capable of dealing with qualitative and quantitative variables simultaneously for studying Costa Rican dairy farmers, their objectives, and how they delegate management decisions.

*Temporal scales:* the importance of temporal scales in characterization studies is sometimes overlooked. They affect several aspects of crop–livestock systems, but two of these deserve special attention. Most researchers tend to concentrate on the time scales of the biological or economic processes — for example, a whole lactation, a crop–growing cycle, rates of biological processes (such as litter decomposition, feed rumen degradation, growth), seasonally fluctuating prices of inputs and outputs, and market conditions. These are very important for defining the system, helping to parameterize models, and understanding the dynamics of the system. Yet the longer time scales that may be used by farm households for setting the management goals for the system in their decision-making process, including considerations concerning the household stage of development (Nicholson and Thornton, 2001), have not received enough attention (Solano et al., 2000b). Much effort has been concentrated on operational decisions (how to supplement cows, how to fertilize crops, etc.) and on identifying strategies for these on the assumption that generating alternative operational solutions will, by default, solve problems operating at longer-term scales. Strategic or tactical planning problems (and solutions) have seldom being studied, and their relationship to family objectives and the way farmers manage their systems are even less well studied, despite the fact that these are crucial aspects to consider for increasing technology adoption.

### 3.2. *Modelling the key components and processes*

The greater complexity of smallholder tropical crop–livestock systems in comparison with other food production systems around the world has been noted above. This complexity poses an enormous difficulty for modelling them, and it is not surprising that there is some scepticism about the potential use of modelling techniques for representing these types of system.

One way to tackle the problem of complexity is through the insight that we do not need to model everything, and that what we do decide to model is largely related to the scale at which we are attacking the problem and the level of aggregation required. Modelling is simply a way of integrating information in a rational way and as such can include a variety of methodologies. Processes and components where we have enough information can be treated mechanistically. Where the quantity or quality of data is insufficient, or in situations where mathematical representation is not currently feasible, we can employ empirical models or rule-based methods. This

approach allows the construction of hybrid models based on a sound scientific platform but with site-specific parameters, and allows the identification of data gaps and research priorities.

Modelling can be a very time-consuming activity. It is thus important to achieve a balance between the level of detail, the precision required, the model's flexibility, and the data requirements.

### *3.2.1. Precision required*

It has sometimes been argued in the past that as long as a model can predict the direction of change correctly when testing a variety of alternative management scenarios, it is satisfactory for decision support and impact assessment. This is a serious misconception, especially when modelling smallholder crop–livestock systems, where the magnitude of errors in component models can substantially change the outcomes of the management scenarios at the farm level and the interaction between components. Consider a 3-ha farm with 10 cows eating a basal diet of maize straw; if a forage intake model deviates from observed intakes by 1 kg per animal per day, this represents 300 kg of fodder per month or 3.6 t per year of straw. Miscalculating the yearly forage requirements by such a margin would probably change the appropriate maize management strategy for achieving the required extra yields, and would probably change the land-use patterns as well. These potential errors would also have important consequences for labour requirements, economic performance and nutrient balances at the farm level. The magnitude of the errors needs to be less than the variance normally associated with the measured variable. Fig. 4 shows an example of the progress achieved in predicting intake of tropical forages with dynamic models of digestion (Herrero, 1997).

In addition to precision, the inclusion of stochastic elements when modelling these systems is of paramount importance, because the occurrence of certain events may have enormous implications for the farm household that far outweigh their apparent probability. For example, the ramifications on household welfare of the death of one cow in a herd of five may be many times those for a household with a herd of 50 cows.

### *3.2.2. Flexibility/applicability*

The flexibility of a model, in terms of the range of situations to which it can be applied, is determined to some extent by its level of complexity and its ability to respond to different inputs. Its applicability is determined by several factors, including data requirements, the components represented, and probably most important in models of crop–livestock systems, its ability to represent management practices. To a large extent it is the complexity of the management options that makes these systems so complicated. In thinking about building generic tools, this is one of the most difficult problems to be solved.

### *3.2.3. Minimum data sets*

Model parameterization and validation are usually the most time-consuming aspects of the whole modelling process. There is a substantial need for developing

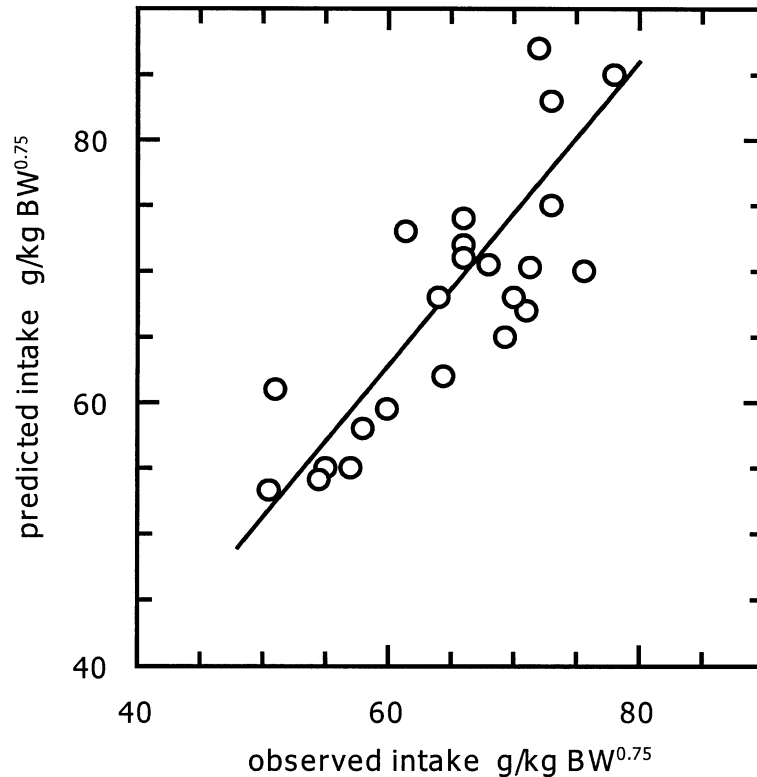


Fig. 4. Predicted and observed intakes of 23 tropical forages using a dynamic model of digestion. Source: Herrero (1997).

minimum data sets for both of these activities to make model use more widespread, especially outside academic circles and research centres. Apart from the driving variables, minimum parameter data sets have been developed for crop and soil models such as DSSAT and Century (Parton et al., 1987, 1994), for example, but less so for livestock and grazing systems models. Herrero et al. (1999b) recently developed minimum data sets for a tropical pasture simulator by carrying out sensitivity analysis on parameter values and selecting those with the highest influence on model outputs. They were able to reduce the internal parameter list from 40 to 10 parameters.

The concept of minimum data sets has usually been applied to specific compartments within a crop or livestock system, but they are seldom defined at the broader, systems level (Hansen et al., 1997). This would require a new level of analysis for identifying commonalities between production systems in different ecoregions and a new set of data standards for allowing comparisons and effective communication between researchers, policy makers and other model end-users. This could be a powerful exercise that could substantially reduce the amount of information required to characterize and define the basic aspects of crop–livestock systems.

#### 4. Scenario analysis and impact assessment

Given an appropriate crop–livestock model, built around the framework outlined above, how might it be used to generate useful information? A consideration of the demand for information shows that many of the problems that face stakeholders with respect to agriculture are systems problems, in the sense that it is very unlikely that their solution is to be both found and implemented by looking at any one component of the system in isolation from the others. This clearly has profound implications for the types of tools that can be used to study them.

Impact assessment, in its broadest sense, is the evaluation of the effects of change in agricultural systems. The change may be brought about by research (a new technology or a new policy) or by a host of other drivers (population growth or market collapse). The effects that may be assessed include changes in production and productivity, income, food security, social welfare, and the environment (Peterson and Horton, 1993). These different effects may also be assessed at different scales, such as the farm, watershed or nation. Impact assessments may have to take some account of the ecological, economic and social subsystems operating at each scale. No one tool or model by itself can possibly be adequate. Thus, most impact assessments that study change that has already occurred (*ex post*) and, particularly, change that has yet to occur (*ex ante*), require mixtures of models and analytical tools to generate appropriate information concerning the effects of this change.

Below, we outline some ways in which crop–livestock models can be combined with other tools and techniques to generate information for impact assessment and scenario analysis, at the household and the regional levels.

##### 4.1. Household level

The modelling framework outlined above describes the crop and livestock components and their interactions in relation to mixed systems. A simulation run then produces outputs in response to a particular set of input conditions, including a particular management scenario. Calibrated and validated models offer the opportunity for scenario analysis, where the analyst can ask and answer ‘What-if’ questions: what if this shorter-season maize variety was grown instead of this longer-season cultivar; what if this kind of supplementary feeding was carried out. This kind of analysis can provide information to answer questions related to the productivity impacts of changes in agricultural systems. These ‘What-if’ questions will relate not only to productivity; if the models are stochastic and respond to the vagaries of weather as expressed in terms of water, nutrient, and disease stresses in the system, then the biophysical risk associated with particular husbandry or management practices can be quantified explicitly. At the household or plot level, it may also be possible to address questions more related to the management of natural resources, such as soil loss or nutrient depletion over time, for example. There is a vast literature concerned with taking crop and livestock model outputs and using them for farm-level economic analysis: gross margins, net returns, partial budgets,

investment appraisals, risky decision analysis, to name but a few (some typical examples can be found in Thornton and Wilkens, 1998).

Such analyses can be extended substantially. The biophysical impacts are clearly critical, but these will translate into effects on household income levels and their variability over time and effects on resource use efficiency by the farmer, as well. Enterprise models can be linked together into some sort of farm household framework, to allow assessment of income and sustainability over time. In the example of Hansen (1996), a farm model was constructed for a smallholder in the Cauca watershed in Colombia, tying together different crop models. Although the livestock enterprises were taken into account using simple relationships with limited interactions with the crop enterprises, the model produced useful information on the sustainability of different options for smallholders being moving out of coffee production, essentially because of low prices.

In this case of an explicit whole-farm model, experimentation can be carried out on an ad hoc basis, allowing a purely exploratory approach to studying impacts of different interventions (in that case, different enterprises and different ways of managing them). Experimentation can also be done using various optimizing techniques including mathematical programming, that explicitly take account of the resource base of the farm and can be used to optimize management and resource use for smallholders' particular objectives. Fig. 5 demonstrates the general rationale behind integrating simulation and optimization techniques for studying crop–livestock

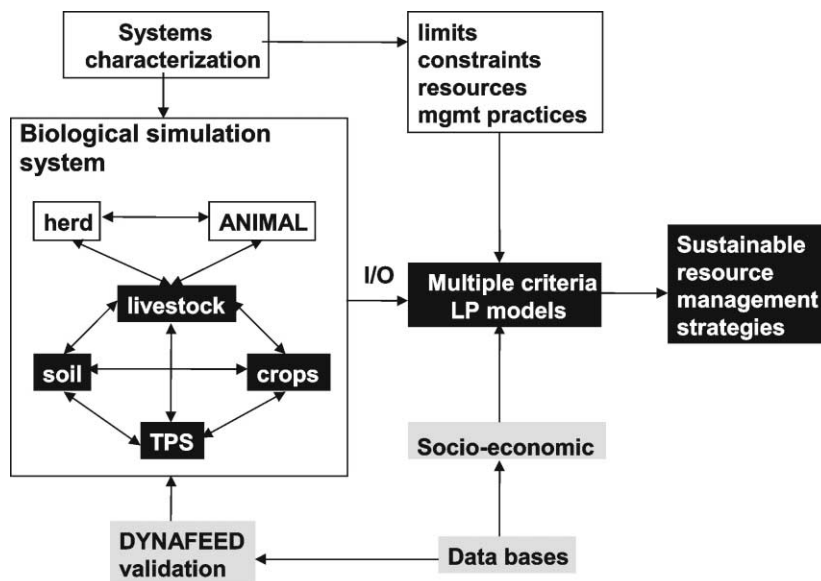


Fig. 5. Integrated methodology for the analysis of resource use and trade-offs in crop–livestock systems. Adapted from Herrero et al. (1996, 1997). TPS, tropical pasture simulator; DYNAFEED, a database of tropical feed quality information for ruminants; LP, linear programming.

systems. In general, these optimizing models of agricultural systems apply mathematical programming algorithms to identify combinations of inputs that may be most suited to a particular set of circumstances. The first step is to use the biophysical model to generate appropriate input–output coefficients which are then fed to the mathematical programming model in the second step. Examples of such approaches are those of Nicholson et al. (1994), Herrero et al. (1999a), Gonzalez-Estrada et al. (2001) and Castelán-Ortega (1999). Nicholson et al. (1994) used a cattle nutrition model to generate coefficients for feeds and animal nutrient requirements, which were then used in a multi-period linear programming model of the dual-purpose cattle productions systems in Venezuela. They found that alternatives to traditional feeding practices are profitable, although dependent on labour availability in these systems. In another example, Herrero et al. (1999a) integrated nutrition, grazing and herd dynamics models with a dairy farm multiple-criteria linear programming model to examine the effects of feeding strategies and grazing management on milk production and land use in dairy systems in the highlands of Costa Rica. They found that suitable strategies existed but depended on the compromise between farm and herd size, and the constraints imposed by milk quotas.

Two rapidly developing areas are the application of global optimization methods and artificial intelligence-based approaches to explore the feasible set of alternatives for impact assessment and management optimization. One approach is the use of genetic algorithms, which mimic natural selection by ‘genetically breeding’ mathematical solutions to optimization problems. Mayer et al. (1996) used such an algorithm to optimize managerial options (such as area of pastures, forage type, and type and level of cow supplementation) in a dairy system in Queensland, Australia. Another approach is the use of neural networks and Bayesian belief networks; an example is described in Walsh et al. (1998), who looked at assessing range conditions in Uganda. Again, biophysical models provide inputs (parameters, coefficients) to the networks for subsequent analysis.

Many factors impinge on the farming system beyond the farm gate. Depending on the questions to be addressed, other systems interactions may have to be included at the watershed or community levels. There is the movement of forage and manure between farms within the watershed, increasingly important for intensifying mixed-dairy systems in some parts of east Africa. There is also the run-off and run-on of water and nutrients that will affect farm-level water and nutrient balances. If the watershed is big enough, land-use and market supply issues may influence local market prices for commodities.

There are various examples of hybrid modelling approaches being used to address such issues (Stoorvogel et al., 1995; Van den Bosch et al., 1998). The spatial arrangement of resources and the spatial nature of resource flows means that spatially explicit models are often required to study them. While mathematical programming models are not themselves spatially explicit, optimization problems can be formulated in such a way as to take account of space at a fairly coarse scale. Crop and livestock models have been linked quite successfully with goal or linear programming models in a spatial context, to study how various socio-economic,

ecological and agricultural objectives can be achieved and traded off against each other (Rabbinge and Van Latesteijn, 1992; Van Keulen and Veeneklaas, 1993). Such methods have been used to study land-use options in west Africa (Van Duivenbooden, 1998) and Latin America (Stoorvogel et al., 1998).

#### *4.2. Regional and national levels*

Impact assessments are often carried out to investigate the effects of technology and policy interventions that have measurable impact on the production and price of commodities. Productivity impacts from simulated model outputs may be aggregated (with care) on the basis of distinct agroecological conditions to give regional or national estimates of production [Thornton et al. (1997) describe an example for a crop], but these usually ignore price effects. A more appropriate approach to assessing the impacts of change at this level is through tools based on the notion of economic surplus.

The basis of the economic surplus model (Alston et al., 1995) is that some sort of technical change occurs that shifts the supply curve of a commodity so that a new equilibrium is reached in the market concerning the supply and demand curves of the commodity per unit time. As the supply curve shifts downwards, consumers become better off than before, because the price of beef has dropped. Farmers may become better off; their unit production costs decrease because of the change, the price they receive from the market will also decrease, but the quantity they are selling will increase. The economic surplus model then values the total benefit arising from the shifting of the supply curve, and this total benefit is then partitioned between benefits to consumers and benefits to producers. In general, the distribution of the benefits depends on the shape and slopes (elasticities) of the supply and demand curves and on the size and nature of the supply shift.

This general model has been extended in a multitude of ways, and as a general technique it has been used widely for valuing both *ex post* and *ex ante* the benefits of research and technology generation. The role that crop–livestock models can play in estimating productivity changes associated with interventions, especially in relation to different agro-ecological conditions and farming systems types (through definition of compact recommendation domains), is substantial. One example is the study of Kristjanson et al. (1999), who evaluated the potential returns to trypanosomosis vaccine research. This involved measuring the potential productivity impact of successful trypanosomosis control using a herd simulation model (Von Kaufmann et al., 1990); linking model results to spatial data bases to determine where the potential increase in livestock productivity from the new vaccine would be likely to occur; and valuing economic returns to this area of research, given various assumptions about probability of research success and adoption levels extrapolated to other parts of Africa where livestock populations are at risk. The potential productivity gains imply that a vaccine could result in a significant reduction in the cost of producing milk and meat for farmers in Africa, leading to increased meat and milk supply worth over \$300 million and a lower price to consumers (Kristjanson et al., 1999).

### 5. From impact assessment to mechanisms for dissemination and promoting adoption: participatory modelling

There are many ways in which crop–livestock models can be used for systems analysis, scenario generation and impact assessment. However, the final test for any of these efforts is successful adoption of the strategies selected, together with resultant beneficial impacts to producers and/or consumers. At current levels of understanding of crop–livestock systems, biologically feasible alternatives are probably easier to identify than to promote. The problem lies in knowing what is attainable within the social and economic organization of a region or country. What is feasible is largely determined by an understanding of the production systems and the farm households managing them. Unless greater efforts are made to increase understanding of the management of systems and to educate the people managing them, models will remain largely within academic circles. One way around this problem is through participatory modelling, i.e. 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.

An example of such an integrated methodology is shown in Fig. 6 (Herrero, 1999). As noted above, the starting point is characterization of the system at different levels of aggregation. At the farm level, data related to land-use practices, crop and livestock management practices can be collected through surveys. The data are then used to identify the main types of production systems prevailing within the selected region, using a multivariate technique such as cluster analysis. Experiments and

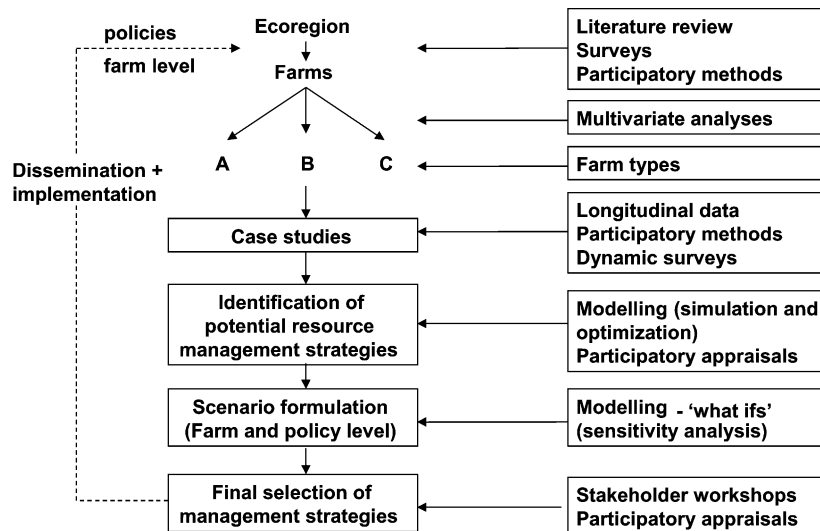


Fig. 6. Methodology for implementing crop–livestock models in the generation and dissemination of on-farm management interventions. Source: Herrero (1999).



longitudinal monitoring of farm household activities, farm management practices, and the economic performance of the systems are carried out in representative farms selected from the system characterization studies. Ex-ante analysis of the strategies tested can then be carried out with regard to the range of different farmers' objectives and attitudes towards risk. Sensitivity to the key management practices are tested for evaluating a range of alternative strategies. Results are discussed in participatory stakeholder workshops, and after perhaps several iterations between stakeholders and researchers, possible interventions for field testing may be identified. The relevant stakeholders may be farmers, extension services, local governments and others. Adoption of strategies is not necessarily related to dissemination and use of the modelling software, but of its outputs. Different stakeholders may require the same information presented in different formats to ensure that the dissemination pathway is tuned to their particular circumstances.

Once appropriate resource management strategies have been selected, these can be disseminated at two levels: farm and policy. At farm level, the selected pilot case study farms can be used as demonstration farms to show the impact of the selected strategies. Farmer groups and extension workers in the regions under study play a key role in the dissemination of outputs through group activities and training courses. Other dissemination pathways may include extension bulletins, pictures, and other media. At a more aggregated level, the bio-economic analysis of the strategies selected can be used to help local governments to target and prioritize their extension policies at the regional level. They can promote the implementation of improved holistic management scenarios through credit schemes for local farming organizations.

The last component of the dissemination phase is monitoring the outcomes and impact of the selected strategies once they are implemented at farm or policy level (Herrero et al., 1997). Stakeholders can examine if target objectives are being met and assess whether re-planning is necessary. Implementation of the methodology then becomes cyclic: as external or other conditions change (weather, prices, access to markets, etc.) the models are rerun for defining the required adaptations, strategies are discussed and selected by stakeholders, implemented, monitored and so on. In this way, participatory modelling can lead to demand-led systems analysis, impact assessment and dissemination.

## 6. Conclusions

There is a considerable need for generic crop–livestock models that conform to the framework outlined in Section 3 to assist in impact assessment. They also have a substantial role to play in helping to translate viable options into management practices that can be disseminated and adopted at the farm household level. Steady progress is being made towards generic crop–livestock models (e.g. see Herrero et al. (1999a, b) and the review of Thorne (1998) concerning the Australian GRAZFEED and the Texas A&M NUTBAL decision-support systems). However, there are some areas that require attention, including the following:

1. Modelling complex crop management strategies (intercropping, leaf stripping, thinning, and other agroforestry practices) used by farmers, and their effects on growth of multiple crop species, crop residues and grain or tuber production.
2. Modelling the impacts of crop management for livestock production on the growth, development and quality of crop parts, such as impacts of leaf stripping and genetic differences in the partitioning of assimilate to grain and stover, and modelling crop residue quality.
3. Modelling the impacts of feed quality and intake on excreta quality (faeces and urine), and the impact of method of manure storage on quality and nutrient return to the production system.
4. Modelling the effects of grazing management on population dynamics and competition between grasses and legumes.
5. Modelling silvopastoral systems and associated management practices, and their effects on grazing management, cattle nutrition and nutrient balances at the systems level.
6. Modelling not only carbon and nitrogen but phosphorus cycles within and between different components of crop–livestock systems.
7. Modelling animal behaviour and diet selection, and their effects on intake and performance of ruminants.
8. Modelling the role of scavenging animals in mixed crop–livestock systems, and developing strategies for improving their contribution to household food security and family incomes.
9. How predictable is farmer behaviour in the management of crop–livestock enterprises, and ultimately does it matter if predictability is low?

The last question is part of what might be termed ‘the intermediate scale issue’. It seems that at the intermediate scales, system complexity threatens to overwhelm the analyst. Spatially, there is uneven understanding of the economic, biophysical and social subsystems at the intermediate levels of the farm household and community. Temporally, there is uneven understanding of the short-, medium- and long-term effects of management options on system performance. While the relative importance of the economic, ecological and social subsystems is highly variable (analysis at the plot level often proceeds, sometimes quite reasonably, in ignorance of the social subsystem that prevails), at the farm level these three subsystems interact in such a way that none can be safely ignored. The difficulty of constructing truly integrated crop–livestock models is at least partially explained by this.

The notion of generic crop–livestock systems models throws into sharp relief various problems associated with inadequate knowledge of some of the processes involved, particularly related to the use of the crop in the smallholder situation, and the necessity of driving such models with appropriate data, i.e. data that are relatively easy to derive and assemble. Even within an appropriate analytical framework, some of the spatial and temporal problems associated with these systems are difficult and will require considerable further work to resolve. Nevertheless, the demand for the information that such models can provide is high. This demand is likely to increase in the future, given the increasing interest in impact assessment and

the projected increases in demand for livestock products the world over during the next 20 years.

## Acknowledgements

Without implicating them in any way, we thank Dannie Romney and an anonymous referee for comments on an earlier draft. All errors and omissions remain our responsibility.

## References

- Alderman, G., Cottrill, B.R., 1993. Energy and Protein Requirements of Ruminants: An Advisory Manual Prepared by the AFRC Technical Committee on Responses to Nutrients. CAB International, Wallingford, UK.
- Alston, J.M., Norton, G.W., Pardey, P.G., 1995. Science Under Scarcity. Cornell University Press, Ithaca and London.
- Baldwin, R.L., Thornley, J.H.M., Beever, D.E., 1987. Metabolism of the lactating cow. II. Digestive elements of a mechanistic model. *Journal of Dairy Research* 54, 107–131.
- Blackburn, H.D., Kothmann, M.M., 1989. Forage dynamics model for use in range or pasture environments. *Grass and Forage Science* 44, 283–294.
- Castelán-Ortega, O., 1999. A decision support system for Campesino maize–cattle production systems of the Toluca Valley in Central Mexico. Unpublished PhD thesis. University of Edinburgh, Edinburgh, Scotland.
- Chambers, R., Pacey, A., Thrupp, L.A., 1993. Farmer First. Farmer Innovation and Agricultural Research. Intermediate Technology Publications, Exeter, UK.
- De Jager, A., Nandwa, S.M., Okoth, P.F., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). I. Concepts and methodologies. *Agriculture, Ecosystems and Environment* 71, 37–48.
- Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., Courbois, C., 1999. Livestock to 2020. The next food revolution. Food, Agriculture, and the Environment Discussion Paper 28. IFPRI/FAO/ILRI.
- Dent, J.B., 1995. Towards a general paradigm for decision making. In: *Proceedings of a Workshop on Sustainability of Central American Production Systems*. Ciencias Veterinarias 1-2 (volumen especial), San José, Costa Rica, pp. 67–70.
- Dent, J.B., Thornton, P.K., 1988. The role of biological simulation models in farming systems research. *Agricultural Administration and Extension* 29, 111–122.
- Donnelly, J.R., Moore, A.D., Freer, M., 1997. GRAZPLAN: decision support system for Australian grazing enterprises. 1. Overview of the GRAZPLAN project and a description of the MetAccess and LambAlive DSS. *Agric. Systems* 54, 57–76.
- Fairweather, J.R., Keating, N.C., 1994. Goals and management styles of New Zealand farmers. *Agric. Systems* 44, 181–200.
- Ferreira, G., 1997. An evolutionary approach to farming decision making on extensive rangelands. PhD thesis, Institute of Ecology and Resource Management, University of Edinburgh, UK.
- Gonzalez-Estrada, E., Fawcett, R.H., Herrero, M., 2001. Modelling as support tool in farming decision making: a case study of a sheep farm in Mexico. In: *Livestock Farming Systems Symposium*, Posieux, Switzerland. European Association for Animal Production (in press).
- Hansen, J.W., 1996. A systems approach to characterizing farm sustainability. Unpublished PhD thesis, University of Gainesville, Florida, USA.
- Hansen, J.W., Thornton, P.K., Jones, J.W., Jacobson, B.M., 1997. Towards data standards for enterprise and farm-level analysis. In: Teng, P.S., Kropff, M.J., Ten Berge, H.F.M., Dent, J.B., Lansingan, F.P.,

- Van Laar, H.H. (Eds.), *Applications of Systems Approaches at the Farm and Regional Levels*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 229–245.
- Hanson, J.D., Skiles, J.W., Parton, W.J., 1988. A multi-species model for rangeland plant communities. *Ecological Modelling* 44, 89–123.
- Herrero, M., 1997. *Modelling dairy grazing systems: an integrated approach*. Unpublished PhD thesis, University of Edinburgh, Edinburgh, Scotland.
- Herrero, M., 1999. Integrating methodologies for analysing crop–livestock production systems. In: Thornton, P.K., Otero, A.N. (Eds.), *Workshop on Ecoregional Research at ILRI-International Livestock Research Institute*. International Livestock Research Institute, Nairobi, Kenya, pp. 87–96.
- Herrero, M., Fawcett, R.H., Dent, J.B., 1996. Integrating simulation models to optimise nutrition and management for dairy farms: a methodology. In: Dent, J.B., MacGregor, M.J., Sibbald, A.R. (Eds.), *Livestock Farming Systems: Research, Development, Socio-economics and the Land Manager*. European Association for Animal Production Publication No. 79. Wageningen Press, The Netherlands, pp. 322–326.
- Herrero, M., Fawcett, R.H., Perez, E., Dent, J.B., 1997. The role of systems research in grazing management: applications to sustainable cattle production in Latin America. In: Teng, P.S., Kropff, M.J., Ten Berge, H.F.M., Dent, J.B., Lansigan, F.P., Van Laar, H.H. (Eds.), *Application of Systems Approaches at the Farm and Regional Levels*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 129–136.
- Herrero, M., Dent, J.B., Fawcett, R.H., 1998. The plant/animal interface in models of grazing systems. In: Peart, R.M., Curry, R.B. (Eds.), *Agricultural Systems Modeling and Simulation*. Marcel Dekker Publishers, New York, USA, pp. 495–542.
- Herrero, M., Fawcett, R.H., Dent, J.B., 1999a. Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models. *Agric. Systems* 62, 169–188.
- Herrero, M., Fawcett, R.H., Silveira, V., Busqué, J., Bernués, A., Dent, J.B., 1999b. Modelling the growth and utilisation of kikuyu grass (*Pennisetum clandestinum*) under grazing. 1. Model definition and parameterisation. *Agric. Systems* 65, 73–97.
- Humphreys, L.R., 1991. *Tropical Pasture Utilisation*. Cambridge University Press, Cambridge, UK.
- Illius, A.W., Gordon, I.J., 1991. Prediction of intake and digestion in ruminants by a model of rumen kinetics integrating animal size and plant characteristics. *Journal of Agricultural Science, Cambridge* 116, 145–157.
- Illius, A.W., Allen, M.S., 1994. Assessing forage quality using integrated models of intake and digestion in ruminants. In: Fahey, G., Jr, Collins, M., Mertens, D.R., Moser, L.E. (Eds.), *Forage Quality, Evaluation and Utilization*. American Society of Agronomy, Madison, USA, pp. 869–890.
- Jansen, D.M., Schipper, R.A., 1995. A static, descriptive approach to quantify land use systems. *Netherlands Journal of Agricultural Science* 43, 31–46.
- Li Pun, H., Jabbar, M., Thornton, P.K., 1999. Ecoregional research at ILRI: background. In: Thornton, P.K., Otero, A.N. (Eds.), *Ecoregional Research at ILRI. Proceedings of a Workshop held at ILRI, Addis Ababa, 5–8 October 1998*. International Livestock Research Institute, Nairobi, Kenya, pp. 1–15.
- Kristjanson, P.M., Swallow, B.M., Rowlands, G.J., Kruska, R.L., De Leeuw, P.N., 1999. Measuring the potential benefits to control African animal trypanosomosis and the returns to research. *Agric. Systems* 59, 79–98.
- Loewer, O.J., 1998. GRAZE: a beef-forage model of selective grazing. In: Peart, R.M., Curry, R.B. (Eds.), *Agricultural Systems Modeling and Simulation*. Marcel Dekker Publishers, New York, USA, pp. 301–417.
- Mayer, D.G., Belward, J.A., Burrage, K., 1996. Use of advanced techniques to optimise a multi-dimensional dairy model. *Agric. Systems* 50, 239–253.
- McDermott, J.J., Randolph, T.F., Staal, S.J., 1999. The economics of optimal health and productivity in smallholder livestock systems in developing countries. *Animal Health and Economics, Revue Scientifique et Technique, Office International des Epizooties* 18 (2), 399–424.
- MacGregor, M.J., Willock, J., Dent, J.B., Deary, I., Sutherland, A., Gibson, G., Morgan, O., Grieve, R., 1995. Links between psychological factors and farmer decision making. *Farm Management* 9, 228–238.

- McInerney, J.P., 1996. Old economics for new problems — livestock disease. *Journal of Agricultural Economics* 47, 295–314.
- McIntire, J., Bourzat, D., Pingali, P., 1992. *Crop–livestock Interaction in Sub-Saharan Africa*. The World Bank, Washington, USA.
- Nicholson, C.F., Thornton, P.K., 2001. Household-level impacts of dairy technology adoption in coastal Kenya. *Agricultural Economics* (submitted for publication).
- Nicholson, C.F., Lee, D.R., Boisvert, R.N., Blake, R.W., Urbina, C.I., 1994. An optimisation model of the dual-purpose cattle production system in the humid lowlands of Venezuela. *Agric. Systems* 46, 311–334.
- NRC (National Research Council), 1996. *Nutrient Requirements of Beef Cattle*, 7th Revised Edition. National Academy Press, Washington DC, USA.
- Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains Grassland. *Soil Science Society of America Journal* 51, 1173–1179.
- Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Anonymous, *Quantitative Modelling of Soil Forming Processes*, Special Publication 39. Madison, WI, pp. 147–167.
- Peterson, W., Horton, W., 1993. Impact assessment. In: Horton, D., Ballantyne, P., Peterson, W. (Eds.), *Monitoring and Evaluating Agricultural Research*. CAB International, Wallingford, UK, pp. 100–107.
- Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), 1995. *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa*. In: *Proceedings of an International Conference held in Addis Ababa, Ethiopia, 22–26 November 1993*. International Livestock Centre for Africa, Addis Ababa, Ethiopia.
- Rabbinge, R., Van Latesteijn, H.C., 1992. Long-term options for land-use in the European community. *Agric. Systems* 40, 195–210.
- Rushton, J., Thornton, P.K., Otte, M.J., 1999. Methods of economic impact assessment. *Animal Health and Economics, Revue Scientifique et Technique, Office International des Epizooties* 18 (2), 315–342.
- SCA, 1990. *Feeding systems for Australian livestock: ruminants*. Standing subcommittee on Agriculture, Commonwealth Scientific and Industrial Research Organisation (CSIRO). CSIRO Publications, Melbourne, Australia.
- Seré, C., Steinfeld, H., 1996. *World livestock production systems: current status, issues and trends*. FAO Animal Production and Health Paper 127. FAO, Rome.
- Shepherd, K.D., Soule, M.J., 1998. Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. *Agriculture, Ecosystems and Environment* 71, 131–145.
- Sniffen, C.J., O'Connor, J.D., Van Soest, P.J., Fox, D.G., Russel, J.B., 1992. A net carbohydrate and protein system for evaluating cattle diets. II. Carbohydrate and protein availability. *Journal of Animal Science* 70, 3562–3577.
- Solano, C., Leon, H., Perez, E., Herrero, M. 2000a. Some aspects of the decision-making process by Costa Rican farmers: 1. Characterising farmers' objective profiles. Paper Presented at Symposium on Systems Approaches for Agricultural Development (SAAD-III), 8–10 November 1999, CIP, Lima, Peru.
- Solano, C., Leon, H., Perez, E., Herrero, M. 2000b. Some aspects of the decision-making process by Costa Rican farmers: 2. Who makes farming decisions? Paper Presented at Symposium on Systems Approaches for Agricultural Development (SAAD-III), 8–10 November 1999, CIP, Lima, Peru.
- Stafford-Smith, D.M., 1992. Applying RANGEPACK to the management of sheep flocks in the Australian rangelands. *Agricultural Systems and Information Technology* 4, 19–20.
- Stoorvogel, J.J., Schipper, R.A., Jansen, D.M., 1995. USTED: a methodology for a quantitative analysis of land use scenarios. *Netherlands Journal of Agricultural Science* 43, 5–18.
- Stoorvogel, J.J., Crissman, C., Antle, J., Bowen, W.T., 1998. A decision support system to quantify trade-offs in sustainable agriculture and the environment in the Andes. In: Thornton, P.K., Otero, A.N. (Eds.), *Proceedings, Workshop on Ecoregional Research at ILRI, Addis Ababa, 5–8 October 1998*. ILRI, Nairobi, Kenya, pp. 123–133.
- Stuth, J.W., Lyons, B.G., 1993. *Decision support for the management of grazing lands. Emerging issues. Man and the Biosphere Series No. 11*. UNESCO, Paris, France.

- Stuth, J.W., Conner, J.R., Hamilton, W.T., Riegel, D.A., Lyons, B.G., Myrick, B.R., Couch, M.J., 1990. A resource systems planning model for integrated resource management. *Biogeography* 17, 531–540.
- Thorne, P.J., 1998. Crop–Livestock Interactions. A Review of Opportunities for Developing Integrated Models (Consultant's Report, Systems Analysis and Impact Assessment Project). ILRI, Nairobi, Kenya.
- Thornley, J.H.M., Verberne, E.L.J., 1989. A model of nitrogen flows in grassland. *Plant, Cell and Environment* 12, 863–886.
- Thornton, P.K., Wilkens, P.W., 1998. Risk assessment and food security. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), *Understanding Options for Agricultural Production*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 329–345.
- Thornton, P.K., Bowen, W.T., Ravelo, A.C., Wilkens, P.W., Farmer, G., Brock, J., Brink, J.E., 1997. Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. *Agricultural and Forest Meteorology* 83, 95–112.
- Van den Bosch, H., Gitari, J.N., Ogaro, V.N., Maobe, S., Vlaming, J., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). III. Monitoring nutrient flows and balances in three districts in Kenya. *Agriculture, Ecosystems and Environment* 71, 63–80.
- Van der Lee, J., Udo, H.M.J., Brouwer, B.O., 1993. Design and validation of an animal traction module for a smallholder livestock systems simulation model. *Agric. Systems* 43, 199–227.
- Van Duivenboden, N., 1998. Development of a methodology to optimise resource-use at village and district levels, with special reference to the desert margins of West Africa. In: *Proceedings of the Methodological Research at the Ecoregional Level Review Workshop held at ISNAR, The Hague, April 20–22, 1998*. International Service for National Agricultural Research, The Hague, The Netherlands, pp. 64–73 (Unofficial publication).
- Van Keulen, H., Veeneklaas, F.R., 1993. Options for agricultural development: a case study for Mali's fifth region. In: Penning de Vries, F.W.T., Teng, P.S., Metselaar, K. (Eds.), *Systems Approaches for Agricultural Development*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 367–380.
- Von Kaufmann, R.R., 1999. Livestock development and research into the new millennium, ILRI working document. International Livestock Research Institute, Nairobi, Kenya.
- Von Kaufmann, R.R., McIntire, J., Itty, P., 1990. *ILCA Bio-economic Herd Model for Microcomputer: User's Manual*. International Livestock Center for Africa, Addis Ababa, Ethiopia.
- Walsh, M.G., Rodrigues-Iglesias, R., Kothmann, M.M., 1998. Bayesian Belief Networks for Range Condition Assessment: Pasture Weed Management in Uganda. ICRAF, Nairobi.