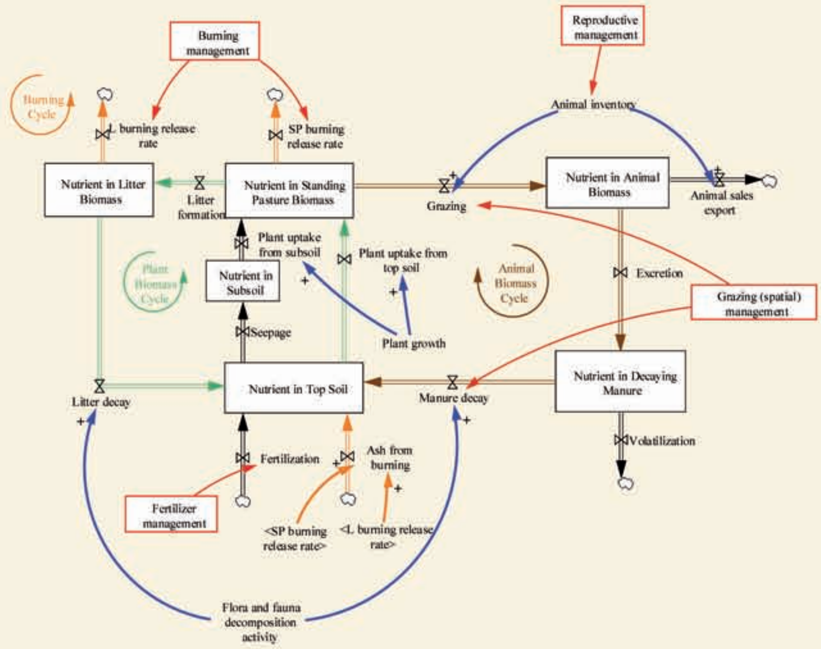
Review of methods for modelling systems evolution



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Cornell University

Discussion Paper No. 3
Targeting and Innovation

INTERNATIONAL LIVESTOCK RESEARCH INSTITUTE

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Executive summary

Acceleration of economic, technological, social, and environmental change challenge decision-makers of various kinds to learn at increasing rates, and at the same time, the complexity of the dynamic systems in which we live is growing (Sterman 2000). In agriculture and international development contexts, there are often significant delays in the development and implementation of technologies and policies, and agriculture-based livelihood systems are in constant and sometimes rapid evolution. In order to make technologies and policies better match the future state of these systems, it is necessary to better understand the likely evolution of agricultural systems. The goal of these efforts should be to improve our understanding about which technologies and policies will be relevant for the state of the future systems so that work can begin on them now. In essence, researchers, policymakers and donors need an improved understanding of general behavioural tendencies for target systems 5 to 10 years hence. Moreover, modelling can be used to assess the impact of specific interventions over a relevant time horizon. Many modelling approaches are available that allow greater consideration of dynamic system characteristics, technology and policy options. These approaches have the potential to allow more dynamic, comprehensive and consistent *ex ante* evaluation of specific interventions, which in turn are one element in the specification of research priorities.

The principal objective of this review is to describe and evaluate conceptual, descriptive and mathematical modelling approaches for the evaluation of systems evolution, emphasizing the potential to include assessment of policy and technology impacts in systems with livestock.[1] To achieve this objective, this document:

- reviews basic concepts in modelling and prediction
- provides an evaluative review of the characteristics of two models designed to predict future global food production and consumption over the next 15 to 25 years
- describes selected conceptual frameworks useful for thinking about systems evolution and
- compares eight modelling approaches—both descriptive and quantitative—that may be used to provide insights about systems evolution and its relationship to technology and policy.

The literature reviewed herein focuses on methods that allow prediction of future behaviour of indicators over a time horizon relevant to help guide technology and policy development. This review also focuses on approaches applied at a scale between the farm and global levels over the time scale of 5 to 15 years. These also could be classified as modelling approaches applicable to the analysis of 'livelihood systems' or 'production systems', in which there is some reasonable degree of homogeneity in terms of the resources, agricultural and non-agricultural activities, and objectives of the agents in the system. Given that no review of modelling approaches can be exhaustive or comprehensive, examples are selected to illustrate the application of the approaches

1. The review focuses on modelling, and not on the theory of systems evolution and induced innovation. It was felt that to cover the theory adequately would add greatly to the length of the document and make the focus rather diffuse.

to agricultural livelihood systems modelling. Delineation of the specific indicators relevant to the predicting systems evolution to provide insights about technology and policy development is beyond the scope of this review. What is important is that the modelling methods allow incorporation of these indicators or objectives in appropriate ways.

For the purposes of this review, a 'system' consists of 'elements' (visible or measurable objects or flows) and 'relationships' (connections postulated to exist between elements). 'Evolution' in this case means a 'behaviour over time' or trajectory. Although point predictions of future outcomes will be relevant, methods can also be useful if they can provide more qualitative predictions, such as behavioural models (e.g. growth, decay or oscillatory behaviours) for indicators of interest or their response to various types of interventions or exogenous shocks. Important characteristics of models include: spatial and temporal scales (aggregation, resolution), time dimension (static, dynamic; discrete/continuous), time horizon, time step, extent to which the model is stochastic, behavioural assumptions (typically of human agents), and interdisciplinary content. Each of these characteristics must be matched with the model purpose.

A number of models have been developed to predict the future evolution of world food systems; the World Food Model (WFM, Bruinsma 2003) and the IMPACT model (Rosegrant et al. 2005) are reviewed herein. Both of these models are dynamic partial equilibrium models with broad commodity and country coverage. The WFM had more disaggregated country and commodity coverage, but relied heavily on expert input and therefore could not be used for analysis of alternative scenarios. This has been subsequently addressed by the partnership between FAO (Food and Agriculture Organization of the United Nations) and OECD (Organisation for Economic Co-operation and Development) to extend the latter's AGLINK to include additional developing countries. The IMPACT model, although sharing some characteristics of the WFM, allowed simulation of alternative scenarios and was used as the basis for the Delgado et al. (1999) publication on the impacts of rapid growth in livestock demand. Predictions about future world food market outcomes are similar between the two models. Both models have limitations with regard to treatment of the livestock sector and could be more fully evaluated in this regard. The discussion of policy recommendations in Bruinsma (2003) is not really linked to policy analysis with the model. Moreover, Döös (2003) presented an alternative to the assessment of the future world food situation based on a complex systems approach, and is sceptical of the usefulness of predictions from models formulated like WFM and IMPACT.

Conceptual frameworks or analyses can be a useful complement to more formal modelling efforts and to suggest, qualitatively, future systems evolution. The frameworks most useful for present purposes include the Colin and Crawford (2000) comparison of alternative economic approaches to systems analysis; the 'kite' framework of Olson et al. (2004) and Maitima and Olson (2006) on land use change; the evolutionary economics framework from Constanza et al. (1993); and the innovation systems approach summarized by Spielman (2005). There is significant overlap in these frameworks, including a) an emphasis on systems approaches, b) the need for better empirical implementation of the general concepts provided, and c) the potential usefulness of both descriptive and mathematical methods. Ultimately, however, an appropriate conceptual framework relevant for analysis of system evolution will depend on the characteristics of the specific system.

Detailed description of past events and an interpretive analysis of the reasons why this evolution occurred (usually expressed in terms of certain driving forces) is another approach to predicting systems evolution. This descriptive *ex post* analysis is then used to make inferences about patterns of future systems evolution, the factors influencing it, and priorities for further study. These descriptive analyses can be related to specific conceptual frameworks, either when a particular framework guides data collection and interpretation or when an objective of the descriptive study is to provide input to develop a conceptual framework (sometimes as a prelude to mathematical modelling). Predictions based on descriptive analyses tend to be more qualitative than quantitative (e.g. general behavioural modes or trends rather than point prediction). Obviously, a key step that determines the usefulness of the descriptive analysis is the ability to infer correctly about future behaviours based primarily on the past. If descriptive studies are to be part of systems evolution studies in the future, care must be taken in their design to ensure that the number and usefulness of predictive inferences are enhanced.

In contrast to descriptive methods, quantitative approaches almost always include specific predicted values (or behavioural patterns) for at least some set of variables. Done well, quantitative approaches have the advantages of rigor, comprehensiveness, logic, accessibility and flexibility. This implies that they are potentially quite powerful predictive tools, particularly when based on adequate descriptive studies. An overwhelming number of basic quantitative approaches and their variants could be applied to assess systems evolution. To keep this task manageable, eight categories of methods have been selected and examples of their application provide an idea of the diversity of their application areas and variants. These eight categories are:

- Statistical analyses (other than time series)
- Time series analyses (distinct from analysis of time series data)
- Dynamic optimization
- Dynamic computable general equilibrium models
- Dynamic partial equilibrium models
- Differential equations-based methods (e.g. system dynamics)
- Agent-based models
- Other simulation approaches (not associated with a particular approach).

In many instances, elements of these basic categories are combined in a single model or analysis. For example, Berger (2001) combined a set of (static) optimizing agents into a dynamic agent based model. Because land use change, climate change and soil degradation processes have received greater research attention with quantitative models, many of the empirical examples applications of the eight methods draw from these areas even if they do not specifically include a livestock component. Important characteristics of the quantitative approaches are their strengths and limitations (either in principle or as usually applied), their data requirements, the effort required for model development (due in part to the availability of commercial software), their ability to be used in a participatory manner, how readily interdisciplinary content (e.g. involve researchers from multiple disciplines) can be incorporated, and the degree to which they can be integrated with other methods. The characteristics of the eight quantitative approaches differ in important ways, which implies different approaches will be most appropriate under different conditions.

Statistical modelling will be most useful in situations where there are adequate time-series data available to test hypotheses about empirical relationships among a set of variables (those relationships presumed to hold in the same manner in the future) and as a basis for parameter estimation for other types of models. The use of time-series analysis may be helpful when longer time series data are available for a limited number of variables of interest, and the emphasis is on prediction alone rather than structural understanding. Variants of time-series methods that include structural variables may be most useful when the periodicity of structural data is significantly larger than that of some phenomenon of interest (e.g. monthly vs. annual data).

Dynamic optimization methods can be useful for understanding systems evolution when a clearly-stated objective for the system can be specified (usually by policymakers). In this situation, optimization models often can identify values of the policy parameters necessary to achieve the objective, resultant outcomes for particular target groups, and marginal resource values. Dynamic CGE models will be most appropriate when the questions of interest are likely to involve general equilibrium effects, such as when agriculture has a significant share of GDP, the scale of the model is national, or when analysis is desired of broader trade or agricultural policy effects.

System dynamics models can be applicable in a wide variety of contexts where the focus is on systems evolution. They will probably be most useful for development of what might be termed 'qualitative quantitative' models in which the objective is to develop relatively aggregated models to enhance initial understanding of the past and potential future behaviour, particularly when data are lacking or a participatory consensus-building process is of interest. Agent-based models also appear to have broad applicability, particularly in situations where heterogeneity of decision-making agents, non-optimizing behaviour and agent–agent interactions are likely to be important. Other simulation approaches, especially integration of multiple simulation models, will be most appropriate when a reasonably high degree of understanding about the various subsystems exists, when the production system of interest has multiple interrelated components, and when sufficient resources are available to support the multi-disciplinary team usually required for these efforts.

Inferences about future behaviours should be made with a good deal of caution for descriptive analyses, statistical analyses and time-series analyses. This is the case because these methods are generally the least able to predict structural changes, tend to be based on a numerical database (rather than broader information sources such as written or mental information), have either limited restrictions on the relationships between variables (for descriptive analyses) or relatively restrictive relationship due to their functional form (e.g. linear regression or time-series models). Dynamic optimization should be employed with care given that relatively few social and economic systems can reasonably be assumed to optimize the values of particular outcomes. Rather, optimization approaches in a systems context are most useful as normative benchmarks.

Dynamic CGE models are most appropriate for addressing a relatively narrow range of non-economic issues at one time (e.g. soil degradation or labour migration as in Glomsød 2001). Their lesser flexibility in incorporating interdisciplinary concepts and the need for an adaptable social accounting matrix (for the relevant production system, rather than a nation, region, or village) will likely limit their usefulness in production systems evolution work in the near future. A key challenge for agent-based models is appropriate specification of agent behaviours and interactions.

The use of integrated models poses challenges similar to those of the more complex SD models in that their calibration, evaluation and use can be more difficult. The required financial and human resources for integrated models should be available prior to their development, particularly because these models can have a relatively narrow (specific) range of appropriate use (e.g. global climate models).

Implications for analysing systems evolution

The ultimate implication of this review can be summarized in terms of the appropriate modelling approaches in given circumstances, implications for systems evolution modelling in general and appropriate follow-on research activities to address systems evolution, technological change and policy options. With regard to the first of these elements, the implications are as follows:

- *No one method is universally applicable or superior.* Each method has advantages and disadvantages, and the applicability of the methods will depend in part on the nature of the problem, outcomes of interest, the information and level of understanding already available, and the financial and human resources available. Often, multiple modelling approaches will be relevant.
- *Systems approaches are preferred if the system is likely to display 'complex' behaviour*. Although no one method is superior in all situations, it has been argued above that when the production system of interest may display dynamically complex (e.g. nonlinear) behaviour over time,[2] the use of a systems approach that emphasizes the development of both conceptual and empirical causal models will be most appropriate.
- *Exercise caution in inferences from descriptive, statistical or optimization studies*. Each of these studies can be useful, but inferences based on each of these approaches independent of others should be made with care.

Implications for systems evolution modelling in general include:

- *Scenario analysis is an important element of systems evolution modelling*. Models to predict systems evolution will be most useful if they facilitate the development of alternative scenarios and their likelihood. The ability to conduct multiple simulations with reasonable turn-around time is an essential part of sensitivity analysis and model evaluation.
- *Systems evolution models will be more useful if they allow assessment of technology and policy options*. The ability to conduct *ex ante* impact assessment in the systems evolution context will be a powerful complement to approaches that make a range of predictions about the future based only on exogenous variables.
- *Greater emphasis should be given to undertaking and reporting model evaluation outcomes*. The purpose of model evaluation, broadly speaking, is to find and correct errors, and to 'build confidence' that the model is appropriate for its stated, specific purpose. Of particular importance are efforts to understand how behaviour over time changes in

2. And as noted above, some authors like Sterman (2000) and Costanza (1993) argued that most coupled human-natural systems have this characteristic.

response to changes in model boundary and omission/inclusion of various effects. In the current literature, these are often present as implied and maintained hypotheses.

- *A broader range of predictive indicators should be employed*. There are at least three kinds of prediction; 'numerical' (point) prediction often can be usefully complemented by assessment of predictions of general behavioural tendencies (e.g. growth, decay, oscillations) and qualitative and quantitative differences that arise due to policy or technology interventions.
- *Greater attention should be given to modelling the impacts of technologies and policy interventions on specific groups, particularly the poor.* For many analyses of systems evolution, it will be appropriate to attempt analyses that disaggregate the behaviours of, and outcomes for, groups of economic agents delineated by income or wealth status.

Areas of future research on systems evolution can benefit from the following:

- *Development of a set of integrated case studies of different production systems will greatly expand our knowledge*. There are relatively few examples in the current literature that have a specific emphasis on prediction of future evolution of production or livelihood systems in agriculture generally or those with livestock more specifically. Thus, development of a series of case studies will be a useful contribution to understanding the future evolution of systems with livestock, enhancing methods to evaluate systems evolution and raising awareness of the importance of this type of work.
- *Systems evolution modelling can benefit from greater participation (and learning) by stakeholders*. The development in the last decade of group model building approaches, simulation games played with participants and 'flight simulators' that allow various types of decision-makers to assess the outcomes of interventions can be powerful tools for linking systems evolution models to effective actions. It also provides a mechanism to facilitate linkages between the often-qualitative participatory research and action approaches, and the nearly-always quantitative approaches of simulation modellers.

In sum, there is a great deal of potential in the various methods described in this document to contribute to an enhanced understanding of the evolution of production and livelihood systems. To fulfil this potential, there is a need for additional systematic research effort and greater attention to the conditions under which the diverse modelling approaches can be usefully employed.

Review of methods for modelling systems evolution

Introduction

Acceleration of economic, technological, social, and environmental change challenge decision-makers of various kinds to learn at increasing rates, and at the same time, the complexity of the dynamic systems in which we live is growing (Sterman 2000). In agriculture and international development contexts, there are often significant delays in the development and implementation of technologies and policies, and agriculture-based livelihood systems[1] are in constant and sometimes rapid evolution. In order to make technologies and policies better match the future state of these systems, it is necessary to better understand the likely evolution of agricultural systems. The goal of these efforts should be to improve our understanding about which technologies and policies will be relevant for the state of the future systems so that work can begin on them now. In essence, researchers, policymakers and donors need an improved understanding of general behavioural tendencies for target systems 5 to 10 years hence. Although this idea is widely accepted, assessment of systems evolution appears to have been addressed infrequently and largely in an *ad hoc* manner in international agricultural research.

An understanding of systems evolution can help to identify general categories of technological and policy interventions that may be beneficial (or detrimental) in the future, so there is an implicit linkage with *ex ante* impact assessment. But modelling methods are needed not just to predict a system's evolution in the absence of interventions (e.g. policy changes or new technologies), but that can assess the impact of specific interventions over a relevant time horizon. The concept of a 'high-leverage' intervention—one that results in sustained positive change in important outcomes—is referred to in some modelling literature (e.g. Sterman 2000). Thus, it is relevant to consider how interventions would influence the post-intervention evolution of the system and subsequent research or policy needs. Based on the review in Thornton et al. (2003), many of the impact assessment methods to date appear to give relatively little emphasis to dynamic systems concepts or the importance of systems evolution in general. The connection between systems evolution and *ex ante* impact assessment can be made much more explicit. Development of systems evolution models that include specific technological and policy options will allow the impacts of these interventions to be evaluated within the context of their ongoing evolution. Many modelling approaches are available that allow greater consideration of dynamic system characteristics, technology and policy options.[2] These approaches have the potential to allow more dynamic, comprehensive and consistent *ex ante* evaluation of specific interventions, which in turn are one element in the specification of research priorities.

Objectives

The principal objective of this review is to describe and evaluate conceptual, descriptive and mathematical modelling approaches for the evaluation of systems evolution, emphasizing the

1. The use of the term 'livelihood system' acknowledges that agriculture is often one element—albeit often an important one—of the means by which rural people earn a living. Other important elements of livelihood strategies include non-agricultural employment (salaried employment or non-agricultural business), off-farm work (e.g. hired labour for others, whether agricultural or not), gifts and remittances from relatives, often children who are educated and migrate from the rural area (Chris Barrett, personal communication, 2005).
2. One example is Nicholson et al. (2004), who developed a conceptual dynamic model of how future technology and policy interventions under rapid demand growth would affect short- and long-term outcomes in the sheep sector of Yucatán, Mexico.

potential to include assessment of policy and technology impacts in systems with livestock. To achieve this broader objective, the document discusses:

- Basic concepts in modelling and prediction, including a discussion of the role of models in the knowledge generating process, model purposes, model types and types of predictions;
- An evaluative review of the characteristics of models designed to predict future global food production and consumption over the next 15 to 25 years;
- A discussion of selected conceptual frameworks that may be useful for thinking about systems evolution, and the importance of such frameworks to empirical modelling;
- A comparative review of eight modelling approaches—both descriptive and quantitative—that may be used to provide insights about systems evolution and its relationship to technology and policy;
- Concluding comments about the relative usefulness of the various modelling approaches to assess the evolution of livelihood systems involving livestock.

The review does not deal at all with theories of systems' evolution and induced innovation, and the interested reader is referred to the considerable literature that exists on these issues.

Definitions and qualifications

It is important to note a number of definitions and distinctions related to the elements of this review noted above. First, there are numerous definitions of both 'system' and 'evolution'. In what follows, 'system' is given a very broad definition based on Meadows and Robinson (1985) as 'any set of interrelated elements'. A system consists of two essential components, 'elements' (visible or measurable objects or flows) and 'relationships' (connections postulated to exist between elements). 'Evolution' in this case means a 'behaviour over time' or trajectory, rather than a 'comparative static' (i.e. non-temporal) analysis or a point prediction for the value of a variable of interest at a specific future time. Likewise, it is relevant to define a 'model' as 'any set of generalizations or assumptions about the world' (Meadows and Robinson 1985) and a 'formal model' as a model in which these assumptions are made explicit through words, diagrams, mathematical equations and(or) computer code.

The literature reviewed herein focuses on modelling methods that allow assessment (either qualitative or quantitative) of behaviours over time on the basis of formal (but not necessarily mathematical) models. Thus, the modelling approaches reviewed must allow prediction of future behaviour of indicators over a time horizon relevant to help guide technology and policy development. It has been quite appropriately pointed out by numerous economists (e.g. Weersink et al. 2004) that a dynamic model will usually involve additional costs and that future outcomes may be reasonably well approximated by a static model under some circumstances. However, there is a growing body of literature on 'complex nonlinear dynamic systems' and 'systems science' that suggests that the circumstances under which static models provide reasonably accurate predictions is limited (von Bertalanffy 1968; Sterman 1991; Rosser 1999).

It is also relevant to consider what is meant by 'prediction' of system evolution. There are multiple types of prediction, but the most common should probably be referred to as 'point prediction' (where interest is focused on a particular value or set of values at a particular time). Although point predictions of future outcomes will be relevant, methods can also be useful if they can provide more qualitative predictions, such as behavioural modes (e.g. growth, decay or oscillatory behaviours) for indicators of interest or their response to various types of interventions or exogenous shocks. This is relevant herein because conceptual frameworks and descriptive models typically do not provide point predictions, but can still be useful to understanding systems evolution. Moreover, it is important to recall that all prediction in science is conditional prediction (Ethridge 1995). That is, with various modelling approaches, we can develop the ability to say 'if X, Y and Z occur, then W will follow'. Unconditional prediction, in contrast, consists of foretelling the future, which assumes that the values of X, Y and Z can be predicted with certainty. Because of the uncertain future values of conditioning variables, all model predictions will be conditional. A subset of conditioning variables are variables assumed to be exogenous for the purposes of the model defines what is sometimes called the 'model boundary' and the degree of endogeneity of a model (Sterman 2000).

Another important element of all modelling approaches concerns the definition of model scale (Costanza et al. 1993; Olson et al. 2004). This is important because it is often the case that the same phenomenon appears different at different scales—even gravity, which has markedly different properties under general relativity vs. quantum theory (Greene 2003). Scale itself has multiple dimensions, but typically refers to the degree of spatial and temporal aggregation for the units of analysis. In much of the literature on 'agricultural systems', that term implies that the unit of observation is the plant, plot, or farm (Colin and Crawford 2000a;[3] Norman and Matlon 2000; Swinton and Black 2000). Various time horizons are employed for analyses at this scale, but it is not uncommon for the analysis to be limited to one growing season or year. At the other end of the spatial–temporal continuum, there are global models (e.g. Alexandratos 1995; Rosegrant et al. 2005) of world food systems that include multiple countries (or regions) and commodities, and which make projections for two decades or more hence.

This review focuses on modelling approaches and examples that have been applied at a scale between the farm and global levels over the time scale of 5 to 15 years. Various classification frameworks might refer to this as the 'meso-scale', the 'regional scale' or 'the community scale'. Alternatively, they could be classified as modelling approaches applicable to the analysis of 'livelihood systems' or 'production systems', in which there is some reasonable degree of homogeneity in terms of the resources, agricultural and non-agricultural activities, and objectives of the agents in the system. These livelihood or production systems may be confined to a limited geographical area or may cross international borders, but they will generally be on a scale smaller than the national. Even at this scale, when analysis of the impacts of policies on income distribution and poverty reduction are of interest, models typically must disaggregate the relevant economic agents to focus on various income or wealth groups.[4] In addition, although specific

3. Colin and Crawford (2000) made an explicit distinction between 'research on agricultural systems' and 'systems science applied to agricultural issues'.
4. This sometimes poses a significant challenge e.g. national- or regional-level data on livestock ownership by income or wealth status do not exist for many countries, complicating efforts to model how technology adoption over time will influence the incidence of poverty.

spatial characteristics (e.g. market access) are often important elements affecting the evolution of livelihood systems over time (Thornton and Jones 1997), these elements are given less emphasis in this review, except as applicable to studies of land use change.

The first reason for the focus on medium-scale, medium-term systems is that, with the notable exception of the land use change literature, this area seems much less well explored in the current dynamic modelling literature than (especially) the plot or farm scale or the global scale. A second reason is that this level of detail and time horizon is frequently the most relevant for the assessment of technological options (given the time frame for their development, dissemination and impact) and policy alternatives (e.g. policy change is often hard to make in the very near term, but neither do many concern themselves with the impacts of policies to be implemented 20 years hence). Market effects arising from the decisions of multiple farmers (processors and consumers) typically influence system evolution and both the short- and long-run outcomes of technology adoption and policy measures. Third, systems at this scale are amenable to more detailed analysis than are global models (at least, for a given level of resources available) and can therefore incorporate additional detail relevant for specific policy analysis, technology assessment and potential endogenous linkages in the system.[5]

This review describes approaches that appear most appropriate for this spatial and temporal scale of analysis, and specific examples of previous research applications focus on those that are medium-scale, medium-term when such examples exist. In some cases, only examples for the farm or national levels and a relatively short time horizon are available, but these illustrate how the methods might be applied to alternative, medium-scales. The basic approach has been to read broadly in the literature on the modelling of agricultural and economic systems, to summarize the key characteristics, strengths and weaknesses of each modelling approach, and to use selected examples to illustrate the application of the approaches to agricultural systems modelling. It is important to note that given the overwhelming number of modelling approaches and models of agricultural systems, this review does not attempt to summarize the broad sweep (i.e. numerous variants, as in econometrics or optimization modelling) nor historical development of these approaches as applied to agricultural systems. Nor is this review comprehensive in the sense of including all potentially relevant approaches or their combinations. In both these senses, it is illustrative rather than exhaustive.

Finally, it is relevant to discuss the criteria by which the strengths and weakness of the various approaches are to be evaluated. In part, this involves consideration of the types of outcomes the models are designed to predict (an output view) and the required resources in terms of time, data, software, technical ability etc. (the input view). It is patently obvious that there are many potential indicators of how a system will evolve, and that no model can hope to adequately account for more than a few of them. This leads to the conclusion that the choice of modelling approach often will depend to a degree on the outcome indictors of interest. Some model developers have adopted the approach of focusing on prediction of indicators commonly used by international organizations to assess developments in specific development-related areas (e.g. Newman et al. 2003; Millennium Institute 2005), but most defined variables in a more *ad hoc* manner. Delineation

5 . As discussed below, many of the global scale models rely on exogenous drivers and limited feedback mechanisms.

of the specific indicators relevant to the predicting systems evolution to provide insights about technology and policy development is beyond the scope of this review. However, it would seem preferable for the selection of such indicators to be based on goals of the CGIAR (Consultative Group on International Agricultural Research) and other international organizations for increasing productivity, alleviating poverty, and sustaining the environment. The specific indicators from these general categories would vary by the production system.

However, what is more important is that the modelling methods allow incorporation of these indicators or objectives in appropriate ways (recognizing that many of the relationships in the system will have imperfect empirical support). This is particularly important when an objective of the model is to assess policies necessary to reduce poverty (although not all modelling efforts to assess systems evolution will necessarily have this as a specific model objective). It will also be important that the modelling approaches allow the inclusion of information from different disciplines into a coherent framework. To a certain extent, the applications of the various methods discussed below also provide examples of potential indicators.

Models and prediction

The principal objective of this document is to review mathematical modelling methods that can be used to predict the evolution of agriculture-based livelihood systems. In part because modelling of various kinds—other than the kind of statistical 'modelling' involved in testing for statistically significant differences under conditions of controlled experimentation—is less frequently practised in the agricultural sciences (and is sometimes disdained as 'not science at all') it is relevant to discuss various aspects of modelling more generally in a document such as this prior to reviewing various modelling approaches. These aspects include the diverse types and classifications of models, the uses of models, the alternative types of predictions that models can provide and more generally, the role of modelling approaches in advancing scientific knowledge. We shall begin with the last—but most basic—of these aspects.

Models and scientific knowledge

Thornley and Johnson (2000), writing about the usefulness of models in plant and crop modelling, stated 'there is then, no difficulty in defending the practice of the techniques, ideas and approaches which we are about to expound'.[1] Ironically, the need for such a statement in the introduction to a textbook on agricultural modelling suggests that in some disciplines modelling in general—or certain types of modelling—are considered an inferior approach to advancing knowledge. This raises the basic question of the relationship between modelling and research. Is modelling an appropriate tool for 'research', defined by Ethridge (1995) as 'the systematic approach to obtaining new and reliable knowledge'? Ethridge argued that 'science' is defined by methodology (the general approach to inquiry in a given field) rather than by methods (the specific techniques, tools, or procedures to achieve a given objective). To paraphrase his assessment of economics:

> Those who exclude modelling as a science because it fails to use a traditional laboratory or because of its range of subjects of study are defining 'science' in terms of the specific methods rather than the methodology.

However, to be legitimate research, simulation modelling must be used according to established criteria for generating 'reliable public knowledge', which Ethridge argued means knowledge that a) can be supported by evidence[2] and b) the way the evidence is obtained can be demonstrated or reproduced. Moreover, modelling work, like all research that generates 'reliable knowledge', must attempt to follow certain essential guidelines applicable to all scientific endeavours. Hence modelling must avoid logical fallacies and should be evaluated using tests of correspondence, logical coherence, clarity and workability, recognizing that the guidelines for implementing and assessing a simulation model relative to these tests are often both vague and subjective.

Modellers of many kinds frequently state that simulation modelling is vitally important to address key issues in social and economic systems, where controlled experimentation would be either prohibitively costly or downright impossible. To modellers, researchers who define 'research' as

1. With apologies for the grammatical awkwardness of this sentence.
2. Note also that Ethridge says that the evidence can be quantitative (data) or 'more complex logical constructions… relationships, generalizations, or deductions/inductions from data', which would thus include simulation models.

including only controlled experimentation are somewhat like the person who has lost their keys at night but is only looking for them in the area illuminated by the street lamp 'because that's where the best light is'. The point is that our conceptions of which methods are most appropriate often lead to a broader perception about which questions are most relevant, interesting, and worthy of funding. It is important to recall that this is not a particularly scientific way of thinking, but it is a reality of the imperfect way in which research priorities are established.

A related issue is the type of research in which simulation modelling is often used. Ethridge described a categorization of research into disciplinary, subject-matter and problem-solving as useful (in contrast to a dichotomy of 'basic' vs. 'applied' research). It seems that much research involving simulation models falls into the 'subject matter' category (i.e. it provides policymakers, decision-makers, and managers with concepts and knowledge with which to make decisions about general sets of problems that they must address) or into the 'problem-solving' category (i.e. it addresses a particular decision process for a specific decision-maker). As a gross—and perhaps unfair—generalization, many of the incentives for academic advancement involve doing disciplinary research ('designed to improve a discipline') that addresses what would be perceived as disciplinary problems rather than implementation or decision problems. This is perhaps another reason why simulation modelling is not as highly regarded it could be as an approach to generating knowledge.

Formal mathematical models, in which assumptions are explicitly written down in mathematical expressions, have many advantages compared to the only other generic model type available for decision-making: so-called 'mental models'[3] (Meadows and Robinson 1985; Sterman 1991 and 2000). These advantages include rigor (assumptions are explicitly stated), comprehensiveness (they account for more information), logic (can reason to error-free conclusions—if the logic is correct), accessibility (they can be shared), and flexibility (can be used to test variety of conditions and policies). Mayer (2002) noted that the development of formal models is often justified because they

- can be used for manipulations and experiments which would be impractical, too expensive, too lengthy or impossible (in real-world social and economic systems)
- can address dynamic complexity (emergence properties) of systems in a way that 'reductionist' science cannot
- can identify 'best management' strategies (through optimization)
- can study the long-term effects of options (e.g. prediction)
- allow the researcher to control environmental and experimental conditions
- allow hypothetical and exploratory situations to be investigated
- allow insight to be gained into the relative importance of different system elements.

Discussing systems-oriented models more specifically, Mayer (2002) stated that such models:

> offer advantages in the study of many scientific and commercial areas, including agriculture. Given the complexity of these systems, a modelling approach is the only

3. Meadows and Robinson (1985) defined a model as 'any set of generalizations or assumptions about the world'. A 'mental model' is 'mental images of the world, of the relationships among its parts and of the influence our actions have on it' (Sterman 1991).

> practical method to evaluate the multitude of dynamic interactions…. In this context, models can be used both strategically (where the best long-term overall strategy for the system is to be determined), and tactically (shorter-term, where the best tactics for the current situations can be evaluated).

Thus, formal mathematical models will often have a useful role in advancing knowledge, particularly in situations in which experimental methods are infeasible or too costly.

Model purposes

Although the focus of this document is on how modelling methods can predict systems evolution, it is also useful to recognize that models have many purposes—and in fact, projections of the future are likely not the most common use of models. Derry (1999) described a number of models, each with a different purpose (Table 1).

Table 1. *Purposes of selected scientific models*

Model	Purpose of usefulness
Ideal gas law	A mechanism to make accurate predictions under 'normal conditions'
Simple blood flow model	A conceptual framework to think about the problem and consider the most important improvements
Nuclear shell model	A starting point for modification of essentially correct but currently inadequate hypotheses
Drug uptake in bloodstream model	A structure to estimate currently non-observable outcomes
Heredity and genetics	A basis for sequential conceptual model development (e.g. from Mendel's peas to the genome)
Game theoretical models	A way to understand human behaviour with mathematics

Source: Based on examples in Derry (1999).

There are other model purposes. Thornley and Johnson (2000) suggested that models are mechanism to integrate and expand existing knowledge, and to identify information priorities to address current (or potential future) problems. Swinton and Black (2000) noted that models have four basic purposes: description, prediction, 'postdiction' and prescription. Models can also serve the purpose of consolidating available information, identifying missing information necessary to gain further understanding, and identifying priorities among missing information (e.g. through model sensitivity analysis). Vennix (1996) suggested that model building directly with groups of stakeholders can build consensus about the origins of problems and preferred interventions. Sterman (1991, 2000) and Letcher et al. (2006a) suggested that the main purpose of models should facilitate learning, in Sterman's words, be 'educational rather than predictive' and 'an essential part of the educational process rather than a technology for producing answers'. The multiple purposes for which models are developed implies that a review of modelling approaches should not focus only on models used specifically for predictive purposes. In addition, model purposes often imply something about the appropriate model type (model characteristics), although it is also the case the multiple model types can be used for a given purpose.

Model types

There exist a plethora of model types, and perhaps only a slightly smaller number of model classification schemes. Prior to discussing specific modelling methods, a general overview of model types is relevant. Meadows and Robinson (1985) identified three principal types of models, each of which is applicable under different circumstances. In the circumstance when a problem is first identified and there is a limited understanding of its basic causes (e.g. 'interconnections that had been considered absent or unimportant may suddenly appear significant') there is a need for models that can contribute to an improved understanding of the basic issues. Such models 'must allow the organization and communication of ideas and hypotheses' and the path by which their assumptions lead to conclusions should be clear. Quantitative precision and excessive detail are 'unnecessary and probably unattainable', so there is a preference for interdisciplinary models with broad model boundaries. This type of modelling, they noted, tends to be more process-oriented than product oriented.

Once there is some agreement about the basic causes of the problem (or the structure of the system generating it), modelling can be used to enhance the efficacy of interventions (policies) to address it. Policy-design models produce conditional, imprecise information, such as 'if this general policy is followed, what will be the general results?' Quantitative precision is more important here than for models of general understanding, but the emphasis is still primarily qualitative and process-oriented. Finally, once a basic policy direction has been determined, models designed to address questions of about detailed policy implementation become most useful. These models must be detailed and accurate, but each one needs to represent only one basic policy direction so its boundary can be narrow. This type of modelling tends to be more product-oriented, difficult, tedious and time-consuming. In sum, Meadows and Robinson (1985) stressed that 'different people sit at various stages of the policy process, asking different sorts of questions requiring different kinds of models'. In order to match the tool to the policy question, one must therefore define the question carefully and must know something about the nature of the tools available.

Existing modelling approaches can be classified according to a number of criteria, including scale, resolution, generality, realism and precision (Costanza et al. 1993). The 'most useful approach' within this spectrum of characteristics depends on the specific goals of the modelling exercise. They claimed that 'a better appreciation of the range of possible model characteristics and goals can help to match characteristics and goals'. Thus, there is a linkage between model type and model purpose. In a manner similar to Meadows and Robinson (1985), (Costanza et al. 1993) noted 'Models are analogous to maps. It is inappropriate to think of models or maps as anything but crude, although in many cases absolutely essential, abstract representations of complex territory. Their usefulness can best be judged by their ability to help solve the navigational problems faced.… It is inappropriate to judge this whole range of models by the same criteria'. At minimum, the three criteria of *realism* (simulating system behaviour in a qualitatively realistic—meaning accurate—way), *precision* (simulating behaviour in a quantitatively precise, although not necessarily accurate, way) and *generality* (representing a broad range of systems' behaviours with the same model) are necessary. Usually, there will be fundamental trade-offs in modelling among these three criteria.

According to Costanza et al. (1993), most economic models can be characterized as *high generality conceptual models*, whereas 'simple linear and nonlinear economic and ecological models have high generality but low realism and low precision'. *High-realism, impact-analysis models* have the objective of developing 'realistic assessments of the behaviour of specific complex systems', and are concerned with accurately representing the underlying processes in a specific system, rather than with precisely matching quantitative behaviour or being generally applicable. Dynamic, nonlinear, evolutionary systems models at moderate-to-high resolution generally fall into this category. In *moderate-generality and moderate precision indicator models* the desired outcome is 'to accurately determine the overall magnitude and direction of change, trading off realism for some moderate amount of generality and precision'.

Many authors, especially geographers (e.g. Olson et al. 2004) have noted the importance of scale for research endeavours including modelling. In this context, the term 'scale' refers to both the 'resolution' (spatial grain size, time step, or degree of complication of the model) and 'extent' (in time, space, number of components modelled) of the analysis. Most real-world processes can be usefully viewed as operating at multiple scales. For example, Swinton and Black (2000) described four scales of importance in agricultural systems: sub-organism, organism, community and aggregated community. Olson et al. (2004) defined a 'Kite Framework' that includes local, national, regional and global scales of analysis. Most mathematical models, however, are specified for a single scale or with limited linkages to other scales. The process of choosing an appropriate scale (or scales) form modelling is directly tied to the problem of aggregation (the process of adding together or otherwise combining components), which in complex, nonlinear, discontinuous systems is far from trivial problem (Costanza et al. 1993).

Rastetter et al. (1992) described and compared three basic methods for aggregation that are applicable to complex systems. They noted that in systems with nonlinearities, many questions arise about the influence of resolution (including spatial, temporal and component) on the performance of models, in particular on their predictability. The difficulty of using aggregate models that integrate over many details of finer resolution models is that the aggregated models may not be able to represent biological processes on the space and time scales necessary. Coupled detailed models (in which the output of one model becomes the input for another) may be a more practical method for scaling models to larger systems. However, 'although increasing resolution provides more descriptive information about the patterns of the data, it also increases the difficulty of accurately modelling those patterns'. There may be limits to the predictability of natural phenomenon at particular resolutions, and scaling rules that determine how both 'data' and 'model' predictability change with resolution (Costanza et al. 1993).

Another distinction between model types concerns the choice of *time dimension*. This includes whether the model is *static* (no explicit time dimension) or *dynamic* (includes a specific time dimension). For dynamic models, the length of the time horizon and the distinction between discrete vs. continuous time are important. The large majority of empirical models applied in agriculture and development (and probably in most other areas of inquiry as well) are either 'comparative static' models or discrete-time models. For the latter, often the time unit of observation is one year or more for aggregated models. Sims (1990) acknowledged that 'the use of discrete time is only an approximation' but that most modellers 'assume (usually) implicitly

that the error of approximation involve is trivially small relative to the other sorts of simplification and approximation inherent' in model development.[4] He noted that some behaviours 'involve discrete delays, and most calculated adjustments in individual patterns of behaviour seem to occur following isolated periods of reflection, rather than continuously' but that this does not necessarily justify discrete-time models. Although he suggested that, in practice, most discrete models are not seriously misleading, is appropriate to give further consideration (and analytical effort) to understanding when discrete-time models are inappropriate.

A minority of models are formulated in continuous time (e.g. models based on differential equations). Even when these models are solved via numerical integration that involves segmenting continuous time into discrete units, these models allow a useful distinction to be made between the choice of *time unit of observation* (e.g. monthly data) and the *time step* (e.g. how finely time will be divided and how frequently calculations will be made). Swinton and Black (2000) noted that in economics 'dynamic models have been little used' in routine applications, and this applies more generally to agricultural systems models at higher levels of aggregation than plot or farm.

Other key distinctions in model types concern whether the models are *deterministic* or *stochastic* (whether input and output variables are based on mean values or a probability distribution) and whether the models are *mechanistic* (based on more detailed representation of underlying processes) or *empirical* (using more aggregated statistical relationships). However, Brown (2000) noted that 'the distinction [between mechanistic and empirical models] is somewhat arbitrary since even the most finely specified theory-driven biological process models are based on some empirically-determined parameters'. Another distinction among model types is the behavioural assumptions, that is, the decision rules used by either individual agents in the system (e.g. farmers) or an aggregated decision-maker (the so-called 'social planner' in some models that seek to maximize well-being in a particular sector). Often the decision rules involve either an optimization decision rule (agents seek to maximize beneficial outcomes or minimize detrimental outcomes) or so called 'rule-based' approaches in which decision-makers respond to given situations with 'rules of thumb' (which are sometimes also adaptable). As implied above, another distinction in this regard is the centralization of decision-making. In some models (e.g. agent-based models, of which more below), decision-making is left to a multitude of individual agents, and outcomes evolve over time in response to these outcomes. In the case of a 'social planner', decisions are made by a single decision-maker, typically with some specific aggregated outcome indicator in mind.

In some literature, models are characterized as 'systems models' but there is no agreed-upon definition of what this means. (As noted earlier, much of the literature on 'agricultural systems models' implies plot and farm level analyses.) Kuiper et al. (2001) noted in a discussion of modelling to assess policy options for more sustainable land use in developing countries, that 'a stream of dynamic simulation models has been developed within an evolutionary economics paradigm, criticizing the reductionist and equilibrium assumptions of conventional economic theory on which most of the models in this volume [the book in which the Kuiper et al. chapter

4. Sims believed that one main reason for the limited application of continuous time models in economics, despite their feasibility, is due to weakness of economic theory in continuous time (e.g. limited statements about the degree of differentiability of most economic time series).

appears] are based'. Although there is a great deal of diversity among the applications of these models—and not all address economic issues—they might be usefully described as 'complex dynamic systems models'. The concepts and conclusions underlying this general school of thought are not frequently applied in models of agricultural systems, but they may prove useful to development of systems evolution models because their focus is almost always on exactly that theme. Batty and Torrens (2005) discussed a number of key themes in this literature, stating:

> Complex systems generate a dynamic, which enables their elements to transform in ways that are surprising, through adaptation, mutation, transformation and so on… the hallmark of this kind of complexity is novelty and surprise, which cannot be anticipated through any prior characterization. All that can be said is that such systems have the potential for generating new behaviours…. Such systems cannot be simplified in the conventional way by reduction or aggregation, for in doing so, the richness of their structure would be lost.

Thus, according to this school of thought, unexpected future developments may arise due to the nonlinear characteristics of the system, past behaviours (and therefore statistical relationships or correlations) may not be a good guide to the future, and simplifying the system through aggregation may ignore essential elements of system structure and possible behaviours. This perspective on modelling extends also to model evaluation, suggesting that neither parsimony nor independent verification are always possible with 'complex systems models' (Batty and Torrens 2005). Some authors suggested that most social, economic, biological and other natural systems could be usefully conceived of as dynamically complex (Rosser 1999; Sterman 2000; Allen and Strathern 2005). With regard to socio-economic systems, Allen and Strathern (2005) believed that 'we now see that socio-economic systems are really complex systems in which various possible structural changes can occur giving rise to a range of different possible futures'. This 'complexity' approach has implications for prediction of future outcomes also. According to Allen and Strathern (2005) 'Today we know that we live in a complex world of emergent behaviour, with attributes in which our powers of prediction are limited'. Even the role of modelling in prediction is called into question in some cases, as in Batty and Torrens' statement that 'complex systems modelling is generative by definition, more a strategy for generating possible model structures and showing their consequences than a technique for developing fully-fledged definitive models with strong predictive capacity'. To a certain extent, this critique of prediction depends on the type of predictive information the model is intended to provide (of which more below).

One final characteristic of formal models is their degree of interdisciplinary content. In reviews of models with both biological and economics components, Brown (2000) and Kuiper et al. (2001) noted that in many models one of these components dominates, due to the challenges of effectively integrating and balancing these components. This is of importance to prediction of systems evolution because many livelihood systems are usefully thought of coupled human and natural systems. Woodward (1998) noted that 'formulating models that are both realistic enough to give meaningful answers to our questions and simple and robust enough to give reliable answers requires partnership between agricultural scientists and mathematicians'. Weersink et al. (2004) noted that there are two basic approaches to integrate different disciplines for model development: interdisciplinary research and coordinated disciplinary research. Interdisciplinary

research requires a great deal of interaction throughout the research process. Researchers from the relevant disciplines collaborate closely in planning and conducting a research project and in arriving at relevant conclusions. An interdisciplinary approach ensures greater consistency between the disciplines, and thereby lessens the risks of making incorrect or inappropriate assumptions. A potential shortcoming of the interdisciplinary approach is a greater degree of compromise between disciplines, making it more difficult to implement in practice. Coordinated disciplinary research involves researchers from relevant disciplines interacting mostly to plan the research and determine the implications of research results, but working independently during the research itself. This approach has the advantage that it enables individual researchers to make use of more advanced disciplinary tools and methods.

Although model characteristics must be consistent with model purpose, there is typically no single model type that can be used to address a given research question or prediction problem. As Woodward (1998) stated, 'There is no one universal methodology [that is, modelling method] that is suited to all problems. The *art* of applied modelling is the ability to synthesise the empirical knowledge and insight of experimental scientists into an appropriate model so that the applied problem can be answered'. This suggests that multiple modelling approaches may be useful in predicting systems evolution, depending on the nature of the system and the type of prediction desired.

Types of model predictions

Just as there are many model purposes and types and not all models are designed for prediction of future outcomes, there are a) ways to predict the future other than formal models and b) different types of predictions that may be of interest. This review focuses only on formal models to evaluate systems evolution and therefore does not evaluate alternative methods such as expert opinion, focus groups, simple trend extrapolation or tarot cards. Perhaps more importantly, the types of predictions that may be of interest can differ and this has implications for the choice of a modelling approach. It is common in the literature discussing dynamic models to equate 'prediction' with what might more specifically be called 'point prediction'. Point prediction refers to the numerical value of a variable or set of variables at a given time (e.g. the temperature in Nairobi, Kenya at noon tomorrow or the future market price of wheat in Alberta, Canada on 27 May 2010). Point predictions are the most specific information (and therefore potentially the most useful) but they are probably the most difficult predictions to make accurately. One reason for this difficulty in point prediction was identified by Sterman (2000) in the context of complex dynamic systems. In nonlinear dynamic systems that are sensitive to small, random perturbations Sterman demonstrated that even perfect knowledge of the system's structure and parameter values will not allow accurate point predictions beyond a certain (often short) horizon. A related phenomenon arises due to errors in the measurement of initial conditions, again even when model structure is known with certainty—which in reality it never is. Sterman goes so far as to suggest that too great an emphasis is given to point prediction in reporting model results and in model evaluation.

An alternative type of prediction focuses on what might be called 'behavioural modes', that is, the general patterns of future behaviour rather than numerical values at a particular moment. Dynamic behaviours can be categorized as one of a relatively small number: linear growth or decay,

exponential growth or decay, s-shaped growth, growth with overshoot (and sometimes collapse) and oscillations. Predictions of behavioural modes indicate which of these modes is likely to occur in the future, for example, whether a variable or set of variables will increase or decrease (either linearly or exponentially) and how rapidly.[5] For variables that are predicted to oscillate over time, the amplitude and frequency of the oscillations may be of interest. Knowledge of future patterns of behaviour, although less specific than point prediction, can still be useful and is probably more accurately predicted (Sterman 2000).

Finally, prediction of the impacts of interventions may be of interest. Often, this takes the form of a policy analysis in which a specific social, economic or environmental policy is to be evaluated, but it can also be considered a form of sensitivity analysis. A frequent goal in this type of analysis is to assess not necessarily the future numerical values of relevant variables or their behavioural modes, but the *differences* in the value of the variables that arise due to the intervention. In some cases, a focus on this type of prediction will allow identification of dominant policy strategies, that is, policies that are superior by some measure to analysed alternatives even given uncertainties about the model structure and future values of the variables. The type of prediction desired from a model influences the choice of should it be explicitly stated as a part of the model's purpose, because it obviously affects the characteristics required.

5. Note this is similar to indicating a *trend* in a variable, but trend often implies linear increase or decrease, which limits consideration of other possible behaviours.

Review of global models of agricultural systems evolution

One perspective on the evolution of agricultural systems with livestock is through modelling of the global food system, that is, use of a model that includes a relatively full set of countries and commodities in one modelling framework. Such a framework should allow for better representation of various interactions on a global scale among crops and between crops and livestock, such as competition for land use, substitution in demand or developments in livestock product trade, and country- or region-specific estimates of interest to policymakers. The two pre-eminent models of this type are the World Food Model (WFM) developed by FAO (Alexandratos 1995; Bruinsma 2003) and the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model developed at the International Food Policy Research Institute (IFPRI) (Delgado et al. 1999; Rosegrant et al. 2005). This section describes basic characteristics of these models and provides a broad evaluation of the modelling approaches. Both models have been in existence for many years and have been revised, updated and employed for various types of analyses. The discussion herein focuses on information related to model versions used to develop the projections of global food production and demand in 2015 and 2030 (WFM) and in 2020 for the IMPACT model, with an emphasis on information provided by the four publications cited above.

The World Food Model

Alexandratos (1995) stated that the main purpose of the development of the WFM was to assess the world food situation in considerable detail to provide a basis for making statements, generally policy-related ones, about the future concerning a) individual commodities, and groups of commodities as well as agriculture as a whole; and b) any desired group of countries. Thus, in its mid-1990s version, the model covered 26 crop products and 6 livestock products in 127 countries. It was noted that 'the above-indicated degree of country and commodity detail makes it possible to use the results of the study to address issues at the most appropriate level of commodity/country interface'. Two additional reasons for this degree of detail were also cited in Alexandratos (1995): 1) that to study problems of natural resource use in agriculture, it is necessary to account for all crops (and presumably, livestock) to address land use issues completely and adequately, and 2) that the interdisciplinary nature of the study could only be fully accounted for if 'the relevant questions are formulated at a meaningful level of detail'.

For these commodities and all countries, FAO made projections for demand (final and intermediate uses), production (supply), and net trade balances (presumably, demand – production). For developing countries only, additional information is generated. This includes:

- Areas, yields and production by country, crop and agro-ecozone
- Livestock numbers (stocks), offtake rates and yield per animal.

Much of the work involved in the modelling process was in creating a consistent set of historical and base year data. This involves what FAO calls Supply and Utilization Accounts (SUA) based on the accounting equation:

Food (direct) + Industrial + Feed + Seed + Waste = Domestic Use =
Production + Imp – Exp + Stocks

The effort required to develop the SUA is emphasized by Alexandratos (1995), who stated

> This is no simple matter as the accounting relationships between commodities range from the fairly simple… to the extremely complex…. Unavoidably, there remain loose ends in the complex accounting framework. FAO has work under way to improve the system and a publication on this matter is in preparation.

When commodity aggregations were desired (e.g. total livestock production), commodities were aggregated using Laspeyres price index (with the same weight for all countries, using world average producer prices at 1979/81 expressed in international dollars).

For crop commodities, production is calculated as area times yield. Aggregate yield estimates for countries are not considered 'good enough', because additional detail on the conditions under which crops are grown is needed. Thus, the FAO model seeks to develop crop estimates by country and agro-ecozone. Because such detailed data are not generally available in any standard data base, the modellers piece them together from various sources. When data for these estimates was unavailable, they 'were supplemented by guesstimates'.

The WFM calculates solutions based on conditions necessary for equilibrium in global food markets. A dynamic partial equilibrium model, it calculates a set of country-level production quantities, country-level consumption quantities, world prices and country-level prices that imply zero net trade flows. Country-level producer prices are calculated as world prices adjusted by the value of the Producer Subsidy Equivalent (PSE, a measure of net producer protection compared to world markets) and country-level consumer prices are calculated in a similar manner using world prices and Consumer Subsidy Equivalents (CSE).[1] However, it is important to note that the model-generated estimates are only initial projections, and cover only a certain number of commodities. As stated in Alexandratos (1995):

> The projections are subject to *many rounds of adjustments (*emphasis added) following inspection by specialists on the basic of the criteria described below. The adjustments are 'absorbed' by the model by fine-tuning its parameters and coefficients, usually trend factors. The model does not, however, have natural resource (land, water) constraints, nor does it generate relevant balances and parameters… the results generated by the model are a major element, but only one among many, which enter the determination of the projections used in this study and only for the cereals, livestock and oilcrop commodities (the WFM commodities). For some other commodities (e.g. sugar, rubber, cotton, jute) single commodity models were used to generate the initial projections, which were subsequently subjected to several rounds of inspection and adjustment.

An obvious issue with this approach is that it makes it more difficult to evaluate the 'model' used to generate the projected values, because the 'model' is really a combination of a mathematical model and a set of 'mental models' provided by the specialists that review the model generated

1. PSE and CSE are parsimonious aggregate measures of differences between world and country prices that result from a variety of trade and domestic agricultural policies. However, they have been criticized as being misleading in certain situations (e.g. in the case of strict quotas; Bishop and Nicholson 2002).

estimate. The combined approach reduces or eliminates a number of the generic advantages of mathematical models (explicit assumptions, logical and error-free conclusions, accessibility and sharing, and ability to test a variety of conditions and policies). As noted in Alexandratos (1995), this method also implies that certain of the mathematical conditions (e.g. consistency between prices and production) in the WFM will no longer apply once the projections have been reviewed and revised. However, the use of expert reviews does allow incorporation of a broader range of information and can enhance model evaluation efforts. Moreover, the process used by FAO is not unique; a similar 'expert review' process is used in other forecast-oriented modelling efforts, notably the Food and Agricultural Policy Research Institute Outlook (FAPRI 2006) estimates of US and world agricultural production and prices. (More discussion of this issue follows below.)

Food demand projections are based on assumed growth in per capita GDP and Engel curves, which generate per capita food demands. These are multiplied by population assumed based on annual growth rates to determine total food demand. These demand estimates are then inspected by FAO commodity and nutrition specialists and 'adjusted taking into account any relevant knowledge or information, in particular the historical evolution of per caput demand and the nutritional patterns in the country examined'. Industrial demands for crops are functions of GDP and(or) population. Alexandratos (1995) noted that historical data are weak for these variables. Feed demand for cereals is derived from 'relationships between variables in the above-mentioned WFM' and 'further checks are performed by multiplying projected production of each of the livestock products with country-specific input–output coefficients (feeding rates) in terms of ME supplied by cereals and brans. The part that can be met by projected domestic production of brans is deducted and the balance represents cereals demand for feed'. Feed demand for oilseeds (based on crude protein) is from the WFM. Feed use for other products is 'obtained by *ad hoc* methods, mostly as a proportion of total production or total demand'.

Once projections of demand, production and trade are complete, the provisional projections are evaluated based on a) the detailed matrix of base-year areas and yields by crop and land class and b) whatever knowledge and judgments the specialists on countries, commodities and the different agronomic disciplines. The objective of this operation is essentially to test the feasibility of the preliminary crop production projections. Similar production analysis procedures are applied to the livestock production estimates. The last step is to project fertilizer use, using a similar approach to that for livestock feed, namely, the use of fixed coefficients for each crop, land class and yield.

The IMPACT model

IMPACT was developed at IFPRI at the beginning of the 1990s 'upon realization that there was a lack of long-term vision and consensus among policymakers and researchers about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base'. The first results from the model were published in 1995, part of a process of further development due to '2020 Vision' project. IMPACT has been used in studies that 'examine the linkage between the production of key food commodities and food demand and security at the national level (importantly for this review, Delgado et al. 1999). It has also been used in several regional studies. The most comprehensive set of results for IMPACT are in Global Food Projections to 2020 (Rosegrant et al. 2001), which provided more detail on the demand system and other

underlying data. This review is based primarily on the information provided in Rosegrant et al. (2005), which emphasized a version of the model that explicitly accounts for water availability, but also the description in Delgado et al. (1999).

There are many similarities between the WFM and IMPACT, but also important differences. In previous versions of IMPACT, there were 36 countries and regions (i.e. about one-fourth the number in the WFM), but IMPACT-Water has further disaggregated data into 282 'food-producing units' (the intersection of 115 economic regions and 126 river basins). The model includes 40 commodities,[2] including six livestock activities and a 'fodder' crop that is not described in detail in the IMPACT-Water documentation.

As is the WFM, the IMPACT model is a dynamic multiple-market, partial-equilibrium framework. That is, it solves for a set of prices and quantities of each commodity in each year that 'minimizes' (in principle, sets to zero) global net trade flows. Prices are the principal endogenous factor affecting future projections. Country-level prices are a function of market-clearing world prices, PSE and CSE values. In addition, IMPACT includes a specific (fixed, exogenous) variable to represent other factors such as transport and marketing costs. Like the WFM, IMPACT provides projections of production, consumption, trade and prices for the commodities it covers (it omits jute and rubber but includes sugar and cotton).

Commodity supply functions for crops are based (as in WFM) on separate functions for harvested area and yield. Harvested area is a function of the own price of the crop, other prices, a trend variable that is intended to represent the effects of population pressure, soil degradation, land conversion to non-agricultural uses, and water availability. Thus, the area function is somewhat more complicated than that in the WFM, but they are not provided in as much spatial detail (i.e. by agro-ecological zone, AEZ). Yield is a function of the own price of the crop, labour availability, capital, water availability, and a trend that is intended to represent various effects: productivity growth (technological change), extension and educational efforts, market access, infrastructure, and irrigation developments. Livestock are modelled similarly to crops, except that the trend variable included in the livestock yield function 'reflects only the effects of expected developments in technology'. Livestock production (defined as 'livestock slaughtered') are a function of own price, other prices, feed prices, and a trend variable. The inclusion of feed prices in the livestock production equation appears to be a difference with the WFM. How milk production (which does not depend on 'offtake' of animal units) is determined is not described in this documentation.

Also similar to the WFM, the IMPACT model specifies demand for food, feed, and other uses. Food demand is a function of own price, other prices, income and population, where income and population growth are exogenous, constant growth rates. Feed demand is specified as a function of livestock production (note: NOT animal numbers, but offtake), exogenous 'feed ratios' that represent the amount of feed per unit livestock production,[3] the feed price and other prices. As in

2. This number is from the text describing the model. One appendix table in Rosegrant et al. (2005) included only 39 commodities and another with detailed commodity descriptions, only 32. This may be in part because this is a preliminary document that has since been updated.
3. Presumably, these ratios are derived from aggregate production data, because this is not a commonly-used measure in the animal nutrition literature, which tends to focus on nutrient requirements per animal.

the WFM, the demand for other uses is more simply specified, in this case as a fixed proportion of the other demands (except for livestock production, which is assumed to be only for food demand).

IMPACT also includes an equation to predict the percentage incidence of malnutrition for children from up to five years old. The equation specifies this percentage as a function of per capita calorie availability (determined by the model), the ratio of female to male life expectancy, a variable indicating the proportion of females of school age enrolled and the proportion of the population with safe water. The variables other than the first are exogenous projections or constant.

Although the emphasis in this review is not on the version of the IMPACT model with water, a brief mention of some of the water-related characteristics is merited. Water is allocated using an optimization approach to minimize 'water shortages' within the water basin. Water demand for livestock is equal to livestock numbers times water required per livestock (i.e. a constant parameter). There is explicit stock-flow accounting for water, which can be carried over from one year to the next. Water for irrigation is assumed to be a residual claimant after industrial and livestock uses. With the water formulation, computational order is to

a) determine crop yields based on prices, labour, fertilizer, other inputs and technological change (assuming no water shortage), then
b) compute water uses for industry and livestock
c) compute crop water availability
d) compute changes in yields and area harvested due to water limitations
e) update crop production
f) calculate global trade balance.

If this balance is not equal to zero, crop prices are adjusted and a new iteration is begun. The process is repeated until net global trade under water constraints equals zero.

Evaluating the global models

Model evaluation is a process (rather than a product) designed to improve the confidence of the modeller and relevant target audiences that the model is appropriate and useful for its stated purpose (Sterman 2000). That is, model evaluation efforts should not be designed to 'prove' that the model is 'correct', because as described below, 'all models are wrong'. Moreover, model evaluation is often conceived of the process of comparing model predictions to historical data (i.e. a focus on 'output') as the primary criterion for model adequacy, when many other tests of the model's assumptions, robustness and sensitivity to changes of model boundary (i.e. a focus on 'inputs') are simply never done. As Sterman (2000) noted, model evaluation should instead 'be designed to uncover errors… [to] understand the model's limitations, improve it, and ultimately use the best available model to assist in important decisions'.

Three points related to model evaluation are worth further discussion. First, the terminology applied to model testing and evaluation varies. Some authors refer to 'validation', others to 'calibration' and others to 'evaluation'. Sterman (2000) criticized the use of the term 'validation' due to its

implication that a model is 'valid' (implying that it is correct) when this can never be the case. Calibration is often, but not always, used to describe the process of choosing (unknown) parameter values that result in model behavioural patterns or point predictions that are deemed acceptable by the modeller. Evaluation, as used in this document, describes a broader, iterative process of model testing designed to improve the model and build confidence that a model is useful for its purpose. Second, models are only appropriately evaluated with respect to their stated purpose, but it is not uncommon in the literature for authors to criticize a model because it does not include a specific component that is not directly related to its purpose. (There is perhaps a fine line between evaluating the adequacy of a model *per se* and evaluating that model's purpose.)

Finally, it is worth noting that there is often a presumption that omission of a particular element known to be important in the 'real world' (or assumed to be so in the disciplinary literature) implies a valid criticism of the model structure. (This is frequently the justification provided in journal articles, e.g. 'previous research ignored this element and this research corrects that omission'). This sort of thinking ignores the fact that ALL models are wrong (even theoretical ones—recall Einstein's revisions to Newton's model of the universe), because they are simplifications of reality. Thus, even an 'improved' model is wrong and it may or may not be 'less wrong' in any meaningful way related to the prediction of relevant outcomes or the other model purposes cited above. Thus, merely citing omitted effects as a justification for an alternative way of modelling something—usually as a maintained hypothesis—is insufficient. In fact, one of the only meaningful ways to evaluate the importance of various model assumptions is to undertake comparative analyses to show exactly how results (numerical, behavioural mode, policy recommendations) differ under alternative model parameters and structures (Fan and Agcaolili-Sombilla 1997 do this in part). This is rarely done in the literature, probably because it involves additional replicative work that is considered 'non-original'.

The evaluation of the WFM and IMPACT models that follows draws upon the model evaluation approach developed in Sterman (2000), which emphasized a variety of criteria and methods. Although not all of these methods can be applied to the two models based on the available information (i.e. in the absence of the ability to run the models themselves and comprehensive documentation), most elements of the evaluation process can be discussed at least qualitatively. In addition to the Sterman approach, additional comments are based on discussion in the documents, especially related to the models' treatment of the livestock sector.

Evaluating the WFM

The basic characteristics of the WFM are summarized in what is called a model boundary diagram (MDB; Table 2). This table indicates which of the variables are endogenous, exogenous and excluded, as well as providing additional basic information such as the time unit of observation. The MBD suggests that although many variables are appropriately endogenized in the model structure, these endogenous estimates are largely driven by exogenous variables for population and income growth. It is worth noting that constant percentage growth rates—even if transformed by other linear coefficients—can only generate one type of behaviour: exponential growth. Thus, the assumed nature of the relationships between exogenous and endogenous variables probably does not allow for much variation in the type of dynamic behaviours the model can generate. The documentation for the WFM in Alexandratos (1995) also seems to suggest that a country's net

trading position is exogenous (i.e. that regime switching is not allowed), which could be a potential limitation for countries with fast-growing agricultural subsectors that could become future exporters (Indian dairy products is one notable example).

Table 2. *Model Boundary Diagram for World Food Model and IMPACT*

Characteristics, Variable Types	FAO (WFM + Specialist)	IMPACT
Characteristics	127 countries	36 countries or region in base
	26 crop products	282 'food-producing units' in IMPACT-Water
	6 livestock products	33 crop products (includes 'fodder', few details)
	Year time unit of observation*	6 livestock products Year time unit of observation
Endogenous	Demand (final and intermediate uses)	Demand (final and intermediate uses)
	Production (supply)	Production (supply)
	Net trade balances	Net trade balances
	Cropped areas (by country and AEZ)	Cropped areas
	Crop yields (by country and AEZ)	Crop yields
	Livestock numbers	Livestock numbers
	Livestock offtake rates	Livestock offtake rates
	Yield per animal	Yield per animal
	Cereals use for livestock feed	Cereals use for livestock feed
	Oilseed use for livestock feed	Oilseed use for livestock feed
	Other products use for livestock feed	Other products use for livestock feed
	Fertilizer use	Fertilizer use
	World and regional prices (see comment below)	World and regional prices
Exogenous	Population growth (constant growth rate)	Population growth (constant growth rate)
	GDP growth (constant growth rate)	GDP growth (constant growth rate)
	Net trade position of country	PSE and CSE values (price wedges)
	Feeding rates (energy- and protein-based) for livestock	Supply and demand elasticities for commodities
	Fertilizer use coefficients	Feed ratios for livestock
		Crop area growth rate
		Yield growth rate (technological change; see below)
		Livestock slaughter growth rate
		Livestock yield growth rate
		Proportion of 'other' (non-food, non-feed demand)
		Marketing costs
		Adjustment parameter (0.5) for feed marketing costs
		Coefficients that determine nutritional status
		Unit water needs for livestock
Excluded	Climate change	Climate change (except water in IMPACT-Water)
	Linkages between agriculture and general economy	Linkages between agriculture and general economy
	Changes in commodity stocks	Change in commodity stocks

Characteristics, Variable Types	FAO (WFM + Specialist)	IMPACT
	Land area in fodder crops Fodder, pasture and other by-products for livestock feed Loss of land due to sea-level rise Greenhouse gas emissions	Loss of land due to sea-level rise Greenhouse gas emissions
Comments	Results are difficult to link to model assumptions directly due to 'specialist input' and the use of other 'single commodity models' for some commodities (sugar, rubber, jute, cotton). A more critical manner in which to view this is as 'results by assumption' in which case the endogenous variables above could be considered exogenous to the model	Productivity growth (technological change), extension, education, market access, infrastructure, irrigation effects on yields are modelled as a single trend term
	Prices are calculated by the WFM to develop initial estimates, but these are no longer consistent with the estimates after adjustment from specialist input	Model assumes year to year equilibrium
	Due to the nature of the specialist input and conceptual issues with development of alternative scenarios, 'model' cannot be used to assess alternative assumptions or sensitivity	Water for irrigation is a residual claimant on total water supplies after industrial and livestock use
	Much effort is expended on development of a consistent set of production and consumption estimates at the country level; this is exacerbated by 'large discrepancies' in the data, especially for trade data. In some cases, discrepancies in the base year data are assumed to persist over the forecast horizon	Demand of commodities for feed use is a function of livestock production (slaughter) rather than animal numbers, which may result in errors if animal numbers are changing in directions different from production. In general, a consistent set of stock-flow (animal numbers offtake) does not appear to be imposed

*Calculations not made for each year.

Another key exogenous factor is the amount of livestock feed per unit livestock. The excluded variables include many natural factors including climate change, but also linkages between agriculture and the rest of the economy. The key strength of the WFM based on the MBD is that it generates production, consumption and net balances for many commodities and countries and changes in land-use patterns in great detail.

A summary of the various model 'tests' (or evaluation criteria) suggested by Sterman (2000) approach complements the information in the MBD (Table 3). Many of the elements of this approach are not reported and it is presumed that the tests were not undertaken. This is particularly true for the output-based measures (integration error, behaviour reproduction, behaviour anomaly and surprise behaviour tests). In part, this derives from the coupling of the WFM mathematical model with specialist input, which effectively precludes most types of sensitivity analysis or alternative scenario assessment. Notable among the elements of the approach that could be evaluated are the limited number of feedback effects (in part because of assumptions about world

food markets being in equilibrium in any given year, which also limits representation of agents' behaviour), the lack of explicit consistency with physical laws, and the basic difficulty of evaluating the model due to role of specialist input.

Table 3. *Model evaluation summary for WFM and IMPACT*

Model purpose and evaluation criterion	FAO (WFM + Specialist)	IMPACT
Model purpose	Provide a basis for making policy-related statements about production and net trade balances for individual commodities and countries by 2015 or 2030	Assessment of global food production and the performance of global food markets by 2020 (roughly 30 year projection horizon)
Boundary adequacy		
Important concepts endogenous in model	Many key variables endogenous, but are essentially functions of exogenous variables (population and GDP growth). Feedback effects are essentially absent	Many key variables endogenous, but are essentially functions of exogenous variables (population, GDP growth and other constant growth parameters). Feedback effects are essentially absent
Model behaviour changes with change in model boundary	Not evaluated or reported	Not evaluated or reported
Policy recommendations change with change in model boundary	Not evaluated or reported	Not evaluated or reported
Structure assessment		
Model structure consistent with relevant descriptive knowledge	WFM structure primarily based on accounting relationships, world market equilibrium assumptions and exogenous growth rates. The extent to which 'relevant descriptive knowledge' from specialists influenced structure or results is not known. Other causal factors excluded	Model structure primarily based on world market equilibrium assumptions and exogenous growth rates. Other causal factors excluded
Level of aggregation appropriate	High degree of regional and product disaggregation is consistent with model purpose	High degree of regional and product disaggregation is generally consistent with model purpose
Conforms to basic physical laws	Not evaluated or reported. It is likely that crop area and yield estimates not explicitly consistent with biophysical effects (e.g. soil quality) and that livestock yields and animal numbers not explicitly consistent with feed availability and use. Changes in stock-holding behaviour excluded	Not evaluated or reported. It is likely that crop area and yield estimates not explicitly consistent with biophysical effects (e.g. soil quality) and that livestock yields and animal numbers not explicitly consistent with feed availability and use

Model purpose and evaluation criterion	FAO (WFM + Specialist)	IMPACT
Decision rules capture behaviour of agents	Market equilibrium assumed in WFM; accounting consistency assumed in overall predictions. No specific agent behaviour is assumed	Market equilibrium assumed. No specific agent behaviour is assumed
Dimensional consistency		
Units of measure for equations consistent without added parameters	Not considered in this review	Units inconsistencies or parameters with spurious units in area response, yield response and animal slaughter equations
Parameter assessment		
Parameter values consistent with descriptive and numerical knowledge	Probably yes, especially given specialist input	Probably consistent with numerical knowledge (e.g. elasticities)
Parameters have real-world counterparts	Probably yes, but not evaluated or reported in detail	Not for some parameters (multiplicative intercepts in area, yield and slaughter functions)
Extreme conditions		
Equations make sense when inputs take on extreme values	Not considered in this review	Not for some equations (e.g. value of 0 for the price of other inputs in crop yield equation leads to evaluation error; value of 0 for the price of other feed in feed demand equation leads to evaluation error; 0 price value in demand for complements in food demand equation leads to 0 demand for food; large marketing cost values can lead to negative producer prices)
Model responds plausibly to extreme shocks, policies and parameters	Not evaluated or reported	Not evaluated or reported
Integration error		
Are results sensitive to the choice of time step or time unit	Not evaluated or reported	Not evaluated or reported
Behaviour reproduction		
Model reproduces qualitative or quantitative behaviour observed	Not evaluated or reported	Not evaluated or reported
Model can generate various modes of behaviour observed	Not evaluated or reported, but likely to produce only linear or exponential growth	Not evaluated or reported, but likely to produce only linear or exponential growth
Frequencies and phase relationships among variable match data	Not evaluated or reported	Not evaluated or reported

Model purpose and evaluation criterion	FAO (WFM + Specialist)	IMPACT
Behaviour anomaly		
Anomalous behaviours result when assumptions of model changed	Not evaluated or reported	Not evaluated or reported
Surprise behaviour		
Model generates previously unobserved or unrecognized behaviour	Not evaluated or reported	Not evaluated or reported
Model successfully anticipates response to new conditions	Not evaluated or reported	
Sensitivity analysis		
Numerical values change significantly with parameter/structure changes	Not evaluated or reported	Alternative scenarios evaluated include slower growth in Asia, greater meat and milk consumption in India, increase in feed conversion efficiency and decrease in cereal feed conversion efficiency. Results are numerically sensitive for some variables
Model behaviour change significantly with parameter/structure changes	Not evaluated or reported	Changes in behavioural mode are not evaluated or reported
Policy implications change significantly with parameter/structure changes	Not evaluated or reported	Not systematically reported, but in general not sensitive for analyses listed above

Note: Evaluation elements based on process described in Sterman (2000).

Alexandratos (1995) provided a cogent assessment of the strengths and limitations of the WFM. In addition to the detailed model outputs, he noted that the involvement of the specialists makes use of a more diverse information set than that based on numerical data alone. However, he also concluded that:

> This heavy dependence on specialist input is at the same time a major weakness of the method…. Projections based on specialist input suffer from the fact that the criteria and assumptions used and the implicit decision-making mechanism cannot be formally described and they can vary from one person to another and over time. *It follows that the projections cannot be strictly replicated at will, including for estimating alternative scenarios by varying certain assumptions only* (emphasis added). This would have been possible only if a formal model had been used for the projections.

Although the input and comments of country, commodity and technical specialists can undoubtedly be helpful to the process of model development, this input is probably less helpful

when viewed primarily as a mechanism to adjust model output rather than address model limitations. (Adjustments to parameter values so that model outputs better match expert opinion should probably not be viewed as significant improvements to the model structure.) In the extreme, it is possible to view this process as 'results by assumption' in which case the endogenous variables could be considered exogenous to the model. A key issue, of course, is the likely accuracy of the specialist input vs. that provided by the formal mathematical model (as well as any weighting that might be applied to two or more different estimates). The perceived accuracy depends in part on the perceived nature of the system that generates the future outcomes. There is a common assumption in the literature based on a dynamic systems approach that many real-world systems can demonstrate rapidly changing or counterintuitive behaviour that is not easily explained or predicted by the experts. As a case in point, Moxnes (1998) examined the ability of various experts (fishermen, biologists, policymakers) in the Norwegian fisheries industry to manage fish stocks sustainably in a computerized simulation model. He found that nearly all of them (including the fisherman) over-exploit the fish resource compared to a sustainable level. Sterman (2000) presented numerous other examples of 'unintended consequences' arising from decisions in dynamically complex systems. As a result of this perception, various authors (e.g. Vennix 1996; Sterman 2000) have concluded that a useful role of experts and(or) other stakeholders is to become more involved in the model development process, particularly through what are called group model-building efforts (Vennix 1996).

Data limitations are one major impediment to implementing a more comprehensive model that relies less on specialist review of the model outputs. Alexandratos (1995) noted that:

> For a formal modelling approach, the choice would be between a roughly estimated formal model with much less commodity, country and land use detail, or a huge model with all the detail of this study but with the bulk of the parameters and coefficients being 'guesstimates' rather than data. The former case is clearly inferior option since it would make it impossible to evaluate the results using specialist input. The second option is really a variant of the expert judgement-based approach used in this study, the difference being that expert judgements would be embodied in the guesstimates of the values of the model parameters and coefficients. Such an approach would be superior to the one of this study, since the utilization of the expert judgement input is subject to the discipline that the implied values of the parameters must fall within a certain acceptable range. Iterations and dialogue would be greatly facilitated, alternative scenarios could be estimated and greater transparency would be assured. These advantages must be set against the greater resources and time required for model preparation, particularly for the development of computing algorithms.

Thus, there was a recognition that a more formal modelling approach would be advantageous, and a key suggested future improvement was to develop more explicit statements of the 'assumed behavioural relationships and their empirical verification, replication of results and derivation of alternative scenarios in a consistent manner'. Although this was a stated goal in 1995, relatively little had been done to modify the model structure for the projections in Bruinsma (2003). As discussed below, however, the FAO and OECD have collaborated on the development of the AGLINK/COSIMO framework as a successor to the WFM.

Data availability is one issue, but another is what is sometimes called 'data reliability' (really, accuracy). Bruinsma (2003), noted that 'errors in historical data become apparent after completing the projections', and that 'large discrepancies often encountered in the trade statistics' (i.e. the sum of world imports is not equal to sum of world exports). In fact, the solution to the problem of trade discrepancies was to assume that a discrepancy of 'roughly equal magnitude' would also exist in the future. This sort of data inconsistency is not uncommon, particularly in developing countries, but the modelling process can still be helpful in identifying these inconsistencies and their implications. The latter information can be derived only if the model can be used to assess the sensitivity of the results to alternative assumptions (i.e. through sensitivity analysis). As noted earlier, one of the advantages of formal modelling efforts is that they can often indicate what information is most important to the prediction of various outcomes. If relatively large changes in an unknown parameter value change numerical, behavioural or policy outcomes by only a small amount, the value of an accurate estimate of that parameter is probably low. Thus, the lack of the ability to conduct sensitivity analyses with the WFM in a context in which data are inconsistent becomes a significant constraint, because the model cannot be used to determine priorities for further information collection efforts.

Bruinsma (2003) also discussed the issue of not using the WFM and its specialist input review process to generate alternative scenarios. The constraints that prevent this are stated as a) the impossibility of forecasting extraordinary events countries may face, the time-consuming nature of estimating alternative scenarios with the methodology of 'expert-based inspection', and more conceptually, defining an alternative set of exogenous assumptions that are internally consistent. The first constraint can be addressed by recalling the conditional nature of the prediction that is associated with all simulation models. The second is undoubtedly an important practical constraint, and a key reason why the model structure has not been further developed to allow sensitivity analyses. An example of the conceptual issue is the relationship between population and GDP. These two variables together define per capita GDP growth, so if population is assumed to grow faster but GDP growth is the same, then per capita growth is assumed to be slowed. Given the complex relationship between per capita GDP and population, the report thus states that 'it would be impossible to define in an empirically valid manner what the relationships could be for each of the more than 100 countries analysed individually in this study'. However, it would seem not inherently impossible to undertake and report various other sorts of sensitivity analyses with the WFM (e.g. changes in technical coefficients rather than exogenous growth rates) and report this information.[4] In addition, providing information on the differences between the WFM estimates and the final projections, perhaps only for regional aggregates and selected variables would also help to evaluate the overall modelling process.

Two final issues merit mention herein. The first is the lack of an explicit linkage between agricultural production and incomes. In the WFM, this linkage works in one direction only: from income to demand to production. Bruinsma (2003) noted that it would be advantageous to include more of these linkages, that is, to transform partial equilibrium models into general equilibrium models. (Dynamic computable general equilibrium models are one approach for predicting

4. In fact, the assumption of exogenous GDP growth rates and endogenous agricultural production in the WFM and IMPACT also raise the issue of the consistency of these outcomes. Computable General Equilibrium (CGE) models are a means to avoid this particular potential inconsistency.

future systems evolution and are discussed further below.) This is not being undertaken because it would require a) too much time and other resources, and b) collection of a good deal more data to develop a consistent 'social accounting matrix' for each country. Given the importance of accurately predicting future food availability on a global scale, however, the potential payoff from improved modelling methods that incorporate more general equilibrium effects and the increasing availability of SAMs that could be modified for general use (through GTAP, for example) the general equilibrium approach probably should not be summarily dismissed.

Finally, the treatment of the livestock sector deserves mention. The WFM is relatively simple in its treatment of dynamics of livestock numbers and livestock feeding. It is not clear whether the WFM as supplemented by specialist input allows for consistent accounting of animal stock (numbers) and flow (offtake) dynamics over the projection time horizon. The use of fixed parameters to convert animal numbers into feed requirements (absent price and other effects) and incomplete treatment of animal feed requirements probably has a non-trivial impact on model predictions for both the feed and livestock sectors. Alexandratos (1995) noted some of the latter limitations, stating that 'these feed-use projections do not provide a complete interface between animal production and feed supplies or resources in each country because of the lack of systematic data for complete feed balances, i.e. including non-concentrate feeds (cultivated fodder, natural grass, by-products other than cereal brans etc.)' As noted above, however, the simplification of a certain model components or their omission is not a valid basis for model criticism. If it were possible to modify the WFM to include more detail with regard to livestock numbers and feeding, assessments could be made of the importance of these simplifying assumptions.

Evaluating the IMPACT model

Because of the similarities in the structures between the WFM and the IMPACT model, many of the comments—other than those pertaining to the use of specialist input—apply to the IMPACT model as well. The MBD indicates relevant endogenous variables (Table 2), which are quite similar to those in the WFM (albeit with less within-country detail, at least for the version from which results are reported in Delgado et al. 1999). The exogenous variables included in IMPACT make use of additional trend variables (e.g. crop area growth rate, livestock slaughter growth rate) not noted in the WFM, nutritional parameters and water usage. Excluded variables are also similar in the two models, except that fodder crops are explicitly included in IMPACT (although they are not discussed in Rosegrant et al. (2005)). Like the WFM, IMPACT is based on the assumption of constant annual growth rates for exogenous variables and year-to-year market (partial) equilibrium. Notably *unlike* WFM, IMPACT can be (and has been) used for various types of sensitivity analysis and for the assessment of various scenarios. This provides IMPACT with a major advantage over the approach that relies on specialist input.

Many of the comments applicable to the WFM in the model evaluation summary table also apply to IMPACT. One area of concern is units inconsistencies or parameters with spurious units in area response, yield response and animal slaughter equations. Some of the intercept-type parameters (e.g. multiplicative intercepts in the area, yield and slaughter functions) have units such as 'ha/($/kg)' or in the case of food demand '$kg^3/(\$^3 \cdot Person)$' that indicate they have spurious units and no real-world meaning. Some of the equations fail extreme conditions tests. For example, a zero

price value in demand for complements in the food demand equation leads to a zero value of demand for food; large marketing cost values can lead to negative producer prices. However, these issues are likely not critically important to the numerical projections generated by the model. In the IMPACT-Water publication, essentially no information is provided about model outcomes, so evaluations of model behaviour are not possible. It is likely, however, that previous publications have explored some of these elements. IMPACT also includes some determination of stocks (unlike the WFM, which apparently ignored them), but stock-holding behaviour and its relationship to prices or other endogenous variables in the model is not clearly delineated.

As with WFM, the representation of the livestock sector is again relatively simple and many of the same potential issues apply. The parameter for feed per unit production is crucial to understanding grain demands for livestock feed. How the match between specific grains and animal species is made is not clear, and must be specified carefully because feed requirements are in fact better related to animal numbers (i.e. not offtake) due to maintenance requirements. Changes in feed efficiency per animal also are specified exogenously (although these are probably better thought of as dependent on diet). Further discussion of the role that fodder production plays in land allocation and animal diets would improve the understanding of the livestock component of the model. Much more easily than for the WFM, additional assessments could be made of the importance of these simplifying assumptions for livestock.

Summary of key findings and implications from the models

Another useful approach to evaluating the global models is to compare their predictions for selected variables. For this comparison, selected livestock production values and growth rates from Delgado et al. (1999) and Bruinsma (2003) are compared (Table 4). Although the comparison periods and point estimates reported are somewhat different, the general pattern is that the predictions of the two models are both qualitatively and quantitatively similar. Key differences are in the growth of poultry meat production in the developed countries (as indicated by differences in the world total), faster pig meat production in the developing countries, and some apparent inconsistencies in the milk production estimates for South Asia. The similarities in results of the two modelling approaches is consistent with the results of Döös (2002), who believed that the assumptions and initial conditions have more influence on the results than the structural differences between the two models.

Perhaps more importantly, the key conclusions and policy implications do not appear to differ between the two models (or, better said, between the discussions based in part on the model results). The key *trends*, as stated in Bruinsma (2003) are that population growth, urbanization, and income growth will lead to rapid growth in demand for livestock products. The key *consequences* are given as:

- increase in developing country share of global livestock production and consumption*
- changing dietary compositions (less cereal, more livestock products)*
- more specialized, intensive production systems
- rapid technological change

- rapid increase in demand for cereal-based animal feeds
- greater pressures on fragile extensive pastoral areas
- increasing livestock disease hazards.

Table 4. *Summary of selected future livestock production values, WFM and IMPACT*

Model (year)	FAO (2003)	FAO (2003)	FAO (2003)	IMPACT (1999)	IMPACT (1999)	FAO (2003)	FAO (2003)	IMPACT (1999)
Reporting year	1997/99	2015	2030	1993	2020	1997/99 to 2015	1997/99 to 2030	1993 to 2020
	Production (× 10^6 t)					% growth rate		
Total livestock production								
World						1.7	1.6	NC
Developing countries						2.6	2.4	NC
Sub-Saharan Africa (SSA)						3.2	3.2	NC
South Asia						3.3	3.1	NC
Total meat								
World	58.7	74.0	88.4	57.0	82.0	1.4	1.2	1.4
Developing countries	28.0	41.2	55.0	22.0	44.0	2.3	2.0	2.6
SSA	2.6	4.3	6.7			3.0	3.0	
South Asia	4.0	5.7	7.4			2.1	1.7	
Bovine meat								
World	58.7	74.0	88.4	57.0	82.0	1.4	1.2	1.4
Developing countries	28.0	41.2	55.0	22.0	44.0	2.3	2.0	2.6
SSA	2.6	4.3	6.7			3.0	3.0	
South Asia	4.0	5.7	7.4			2.1	1.7	
Pig meat								
World	86.5	110.2	124.5	76.0	122.0	1.4	0.8	1.8
Developing countries	49.3	69.5	82.8	39.0	81.0	2.0	1.2	2.7
SSA	NC	NC	NC			NC	NC	
South Asia	NC	NC	NC			NC	NC	
Poultry meat								
World	61.8	100.6	143.3	48.0	83.0	2.9	2.4	2.0
Developing countries	31.3	59.1	93.5	21.0	47.0	3.8	3.1	3.0
SSA	0.9	1.9	4.1			4.3	5.1	
South Asia	1.1	3.9	10.6			7.9	6.9	
Milk (whole milk equivalent)								
World	562.0	715.0	874.0	528.0	772.0	1.4	1.3	1.4
Developing countries	219.0	346.0	484.0	164.0	401.0	2.7	2.3	3.2
SSA	16.0	26.0	39.0	10.8	31.0	3.0	2.8	4.0
South Asia	104.0	174.0	250.0	132.2	218.0	3.1	2.4	1.9

Note: 'NC' means not calculable from reported data. For some reported values of production, growth rates were calculated as constant growth rates. For some reported values of growth rates, production was calculated assuming constant growth rates.

Although none of these conclusions is particularly counterintuitive (and probably not controversial), it is worth noting that only the first two (marked with an '*') have been assessed (in contrast to assumed) within the formal modelling framework. Bruinsma (2003) discussed that these consequences is largely descriptive, without much citation of additional (i.e. non-model) evidence. Bruinsma (2003) also discussed likely developments in the various livestock production systems (grazing, crop–livestock, intensive/industrial), but again these appear not to be tied to the projections in any formal modelling sense (although they may be accounted for to a certain extent

as a part of the specialist input into evaluation of the model scenarios). The discussion of major policy issues and possible policy responses includes the following rather lengthy list of issues:

- economic development and poverty alleviation
- financial and technical barriers (risk, transactions costs) to livestock technology adoption
- animal health
- animal welfare
- feed quantity* and quality
- livestock and trade*
- food safety and zoonoses
- antimicrobials/hormones
- livestock biotechnology
- genetically modified organisms (both livestock and feeds)
- environmental issues
- genetic diversity of livestock populations.

The discussion in Bruinsma (2003) is again largely descriptive and is only linked to the projections for two of the categories (indicated with an '*'), because the model does not contain many of the elements listed above and even for those elements it includes, it cannot predict alternative scenarios or conduct policy analyses. This is not necessarily a criticism of the modelling *per se*, because the models do not have the stated purpose of addressing these issues. However, the listing above is designed to illustrate that there are a relatively large number of important livestock policy issues a) that are not being incorporated in the global analysis models and b) for which global policy recommendations (at least generic ones) are apparently being formulated without formal modelling analyses. In Delgado et al. (1999), much more additional evidence is cited during discussion of these issues, but this does not alter the fact that many of these conclusions do not, in fact, derive from a consistent, comprehensive modelling framework. Although this is understandable to a certain extent, it is somewhat more a concern that policy recommendations in the documents associated with the modelling work are not based on policy analysis with the models. In Bruinsma (2003), for example, the key policy recommendations are:

- removal of policy distortions
- building of institutional and infrastructural capacities to allow small-scale rural producers to compete and integrate successfully within the developing country livestock industry
- develop a conducive environment through public sector investment where necessary, to allow producers to increase production through improved efficiency and productivity
- work towards effective reduction of environmental, animal and human health threats.

These recommendations may also fall into the category of being broad enough (alternatively, vague enough) that they are beyond controversy, but it is essential to recognize that these recommendations are not based on specific policy analyses with the FAO model (which as noted above, is used only for generation of a single projection). One of the key limitations of the global modelling work to date, it seems, is that the attention to detail at the commodity and country level (and in the case of FAO, the use of specialist input to a high degree to address data quality and consistency issues) results in relatively limited prospects for policy analyses for the livestock sector more generally, and for future technology development and policy priorities more specifically. The IMPACT analyses of changes in feed conversion efficiencies are a start in this direction, but they are highly aggregated into a small set of parameter values and in any case do not suggest how such changes might be brought about. In particular, the current global modelling efforts do not address issues of disaggregating the overall effects by relevant categories of livestock producers (e.g. smallholders) so that more specific technology and policy options can be designed. The global models do not have such issues as their stated purpose, so it is not appropriate to criticize them on that basis. However, it is obviously necessary to develop complementary analyses (some of which might use FAO and IMPACT outputs as starting points) for more detailed predictions and policy analysis at the country and regional levels.

An alternative evaluation of models to predict global food production

Döös (2002) offered a more critical and pessimistic review of all efforts to predict future global food production (including some discussion of the WFM and the IMPACT models) under the assumption that the global food system is likely to demonstrate complex dynamic behaviour. A meteorologist, Döös begins by noting that even for simple dynamic systems (e.g. a system of three differential equations representing a simple climate system, Lorenz 1963) with perfect information available for model specification, small errors in definition of the initial conditions will imply that our ability to predict the longer-term future will be quite limited.[5] This pessimism is due to a common property of nonlinear dynamic systems: sensitive dependence on initial conditions (Gleick 1987).

In contrast to the rather reductionist approach taken by the WFM and IMPACT, Döös (2002) developed an underlying conceptual (causal) model that identifies the factors that have a significant influence on food production, then opined about how well they can be predicted at present and how well they likely could be predicted in the future (Table 5). His basic conclusion was that practically none of the factors having an important influence on food production can be specified with a high degree of accuracy, due to insufficient knowledge of processes (e.g. soil degradation and(or) insufficient data). In addition, nonlinearities can lead to unexpected, rapid developments. As he stated, 'Even small, gradual changes in the forcing conditions of the earth system can, through complex nonlinear interactions and feedback processes, result in significant and rapid changes and surprises'.

In the face of the limited current accuracy of predictions of these causal factors, Döös (2002) suggested that one approach to model future world food production is to take rates of change in these various factors into account, ignoring any interacting processes among them. In a sense, this

5. Based on his three-equation model of weather systems, Lorenz is reputed to have remarked that from that first day, he decided that long-range weather prediction was doomed.

is how the WFM and IMPACT models work, although they include only a limited number of the causal factors and simplified representations of most factors other than the impacts of prices and economic growth. The estimates generated by these simpler 'rates of change models' will have lots of uncertainty, but then the question is 'Can more "sophisticated" modelling efforts—models that account for the interactive processes—do any better?'

Table 5. *Summary of predictive accuracy of factors affecting global food production*

Factors	Current prediction accuracy	Future prediction accuracy
Driving forces		
Population growth	M	M
Socio-economic developments (e.g. GDP growth)	L	L
Management and new technologies	M	M
Greenhouse gas emissions[1]	M	H
Climate change (temperature, precipitation, variability)	L to M	L to H
Yields and cropping index		
Fertilizer use	M	M
Irrigation and salinization	L	M
Biotic stresses (diseases, pests, weeds)	M	M
CO_2 fertilization effect	L	M
Agricultural land use		
Loss of agricultural land to other uses	M	H
Loss of agricultural land due to sea level rise	L	M
Soil degradation and erosion	L	M
Use of land currently in forests, pastures or other non-agricultural uses	L	H
Natural disasters (tropical cyclones, earthquakes)	L to M	L to M

L = Low; M = Medium, H = High.
1. Döös (2002) did not explain the rationale for greenhouse gas emissions as a driving force, but presumably it reflects influences on the earth climate system and perhaps on policy initiatives.
Adapted from Döös (2002).

A more sophisticated (i.e. integrated, causal) model would need to include four components, according to Döös (2002). The first would be a representation of the driving forces, which he suggests are so unpredictable that it is probably preferable to use exogenous estimates (e.g. of income growth and population change, as done in the WFM and IMPACT). The second would include 'earth system' processes (physical, chemical and biological processes—including climate change—that have an influence on food production; these effects are largely absent from WFM and IMPACT). A third component would explicitly address the factors affecting food production (changes in land use and yields for crops and pasture (and presumably livestock) and the assessment of the relationship between food production and food demand. This component is the centrepiece of the WFM and IMPACT models, although the relationships are still rather simplified due to data limitations and the desire for broad country and commodity coverage. The final component is described as an 'adaptation-mitigation' module, which identifies opportunities and responses for modifications of agricultural practices and crops in the face of climate variability. Neither WFM and IMPACT contain these elements (with the possible exception of water resources in IMPACT-Water). For such a model to be useful, it requires a longer prediction period (probably 30 to 100 years), but can have a lower resolution in terms of country and commodity coverage. As Döös (2002) noted, 'Detail may well be important for comparatively short prediction periods, and if the data can be considered to be reliable. However for predictions over longer periods (4–5 decades) the demand for a high degree of detail can hardly be justified'.

Ultimately, Döös was most pessimistic about socio-economic models, considering them a sort of weak link in the chain of the four modelling components required.[6] As he put it, 'Causal models of social and economic processes have large uncertainties and pose problems which may be of a qualitatively different character than those associated with modelling nonhuman components'. As a result, models are to be developed to predict future food production, he suggested limiting linkages (feedback) between the driving forces (population growth, income growth, new technologies and greenhouse gases), the earth system and food production, because in many cases there is 'little or no feedback between food production and the driving forces'.

As an alternative to efforts to predict future world food production (presumably, what might be called 'point estimates') he suggested that modelling can be most useful to assess the sensitivity of food production to the changes in various influencing factors. This information could then be used to identify 'weak points' in the world food system and to 'develop response measures', recognizing that long lead times for decision-making and (biophysical) response times are likely to be necessary. Ultimately, this implies a focus for modelling efforts on mitigation and adaptation strategies, rather than prediction *per se*.

6. This opinion is not unique to Döös. Many other natural and physical scientists share this scepticism about the ability of economic model predictions (Steven Strogatz, Department of Theoretical and Applied Mechanics, Cornell University, personal communication).

Conceptual frameworks or models

Discussion of conceptual frameworks or models is important for two reasons. First, conceptual models can provide relevant insights about the likely future dynamics of a system under certain conditions. Second, both descriptive and empirical modelling efforts are frequently linked to a particular conceptual framework, which often defines the scale, variables of interest and in the case of mathematical models, the mathematical approach. However, the use of the conceptual framework is inconsistent for modelling work on agricultural systems, perhaps in part because many believe that 'modelling in agricultural research is essentially an empirical process, with only few feasible theoretical considerations' (Vohnout 2003). Some authors have argued that 'no… research endeavour should be undertaken without… a conceptual framework for the project' (Ethridge 1995). The purpose of this section is to provide a definition of the conceptual framework, to provide comparative examples of how alternative conceptual frameworks can lead to different research emphases and to summarize a selection of conceptual frameworks that may be useful to the examination of systems evolution.

Conceptual framework definition

The conceptual framework (CF) is a conceptual analysis through the problem to all hypotheses relevant to the problem (Williams 1984). It is purely conceptual (logical), that is, without regard for empirical evidence or data. The conceptual framework may be viewed as an analysis of the research problems using theory, where the 'theory' may be derived from a variety of disciplines. The CF will often provide a conceptual linkage between the research objectives and the appropriate methods and analyses, but it is more than a justification for a specific procedure. The conceptual analysis will typically identify relationships, or types of relationships, that are needed to explain a phenomenon, and also indicate variables of interest. Williams (1984) characterized the CF as an organized 'think piece' that in its analysis of the research problem, includes identifying:

- sources of the problem (conditions, circumstances, policies, practices etc. that cause(d) the problem)
- variables relevant to the problem
- conceptualized relationships in a system to analyse the problem
- hypotheses to be tested about results of analysis of the problem.

It should be noted that in many of the examples that follow, often there is an 'analytical framework' that describes the basic approach taken to addressing a particular research question, but it is not a CF in the Ethridge (1995) sense because it does not fully develop an analysis of the problem, the specific relationships or hypotheses to be tested. As is the case for the overall review, the basic approach has been to read broadly in the literature and to select contrasting examples of conceptual frameworks applied to agricultural systems evolution.

Conceptual framework examples

Boserup agricultural intensification framework

Much of the literature on agricultural intensification describes the 'inevitability' of rising population density driving the intensification of agriculture toward the greater integration of crops and livestock, for example, based on the ideas developed in Boserup (1965, 1981). Numerous other authors have adopted or adapted this framework, including Pingali et al. (1987) who used it as a basis for analysis of the adoption of animal traction in sub-Saharan Africa (SSA). This conceptual model posits an 'evolutionary' theory of farming systems, suggesting causal factors of change (e.g. population growth and accompanying land scarcity), the direction of change (greater integration and productivity per unit land) and a sequence of stages through which agricultural system is assumed to pass. Empirical assessment of the theory has relied primarily on cross-sectional studies of various farming systems with the assumption that they represent points along a limited number of evolutionary paths.

However, Wolmer (1997) pointed out that 'there are… serious dangers in reading spatial environmental differences as evidence of historical change', and postulates that a variety of other factors are important to explain the process of crop–livestock integration, including: market proximity, national government policy, structural adjustment programs, and changes over time in trypanosomosis threat. Wolmer (1997) noted that a variety of trajectories exist for changes in the role of livestock in integrated systems. Some of these trajectories are not examined under the Boserup (1965, 1981) models nor are they considered consistent with the Boserupian hypothesis. In addition, there appears to be an implicit assumption that the Boserupian CF implies sustainability (i.e. the systems are sustainable and unchanging after the sequences of stages have been passed through), and some authors have argued that 'there is no reason to expect a relationship between intensification, or crop–livestock integration, and environmental sustainability'. As a result of what are viewed as limitations of the Boserup (1965, 1981) CF, Wolmer (1997) proposed an alternative 'actor-orientated' approach that: begun with a detailed understanding of the strategies and trade-offs of different social actors, recognized the importance of social differentiation, included study of the evolution of institutions that mediate change, and highly disaggregated (rather than averaged) indicators of actor characteristics and resources. These alternative approaches suggest different methods and possibly different projections of the future.

More specifically for the purposes of predicting future systems evolution, Boserup's (1965, 1981) intensification model attempts to describe long-run processes of intensification as driven by population growth and farmers' assumed preferences for leisure (Lambin et al. 2000). The model is essentially applicable only in subsistence agricultural systems and is valid for the 'broader sweep of agrarian change history rather than for individual, local cases', according to Lambin et al. (2000). As a result, they deem it 'hardly suitable for prediction'. Thus, it constitutes a largely verbal and not spatially explicit model that was not designed for numerical prediction. As noted above, however, the validity of this line of criticism depends on a) the degree of accuracy vs. precision desired from the model, and b) the model purpose (i.e. how specific a prediction is desired). The model primarily provides a basis for empirical testing of key hypotheses and future predictions, rather than a prediction approach *per se*.

Olson et al. (2004) land use change framework

Olson et al. (2004) described an 'analytical framework' with the objective of understanding the 'root causes' of land use change (and presumably, predicting future changes). They noted that numerous previous frameworks (e.g. neoclassical economics, cultural ecology, political economy, political ecology, and landscape ecology) have been used to address 'society/environment interaction' of which land use change is a notable example. They developed an analytical framework that combines elements of all of these different approaches. The key *principles* of their framework are:

- Integration of environmental and societal processes (sometimes also described as 'linked human-natural systems'), recognizing that these processes have different spatial and temporal scales;
- Use of an historical time frame to understand the temporal (dynamic) dimensions of the problem and examination of interactions across space;
- Allowing for the possibilities of bi-directional (often feedback-driven) change;
- Explicit examination of both 'top–down' and 'bottom–up' processes and the connections across sectors (the interactions between sectors and scales);
- Recognition of the political and economic power differences among individuals and communities and that these differences will affect outcomes and policies.

Collectively, these principles imply a framework based on an interdisciplinary systems approach that will employ various data sources and methods. The key *processes* that are hypothesized to influence land use change are globalization, national policies on land tenure and land access, civil strife and insecurity, income diversification and urbanization, gender roles and labour allocation, and poverty.

Heerink et al. framework on sustainable land use

Heerink et al. (2001a) described a general 'analytical framework' to assess the impacts of various policies (primarily economic policies) on the sustainability of land use. They distinguished four levels of analysis: the macro level, socio-economic environment of the farm household, the farm household and the field or plot level. They noted that there are feedback processes among the different levels, and focused much of their discussion on factors affecting household decisions (relative prices of inputs and outputs, land tenure systems, social capital, customs and norms, market access and transactions costs), which comprise the socio-economic environment and which are influenced by policies made at the macro level. Policy changes can have a large impact on this socio-economic environment. At the field or plot level, they highlighted that land degradation comprises different processes, including soil erosion by wind and water, chemical deterioration and physical deterioration, and that feedbacks between soil degradation and household decision-making 'can be' added depending on the model purpose. The framework is ultimately too general for specific model development, and generally adopts a neoclassical economics approach to the issue.

Heerink et al. (2001a) made an explicit linkage between their analytical framework and a number of 'modelling approaches', focusing primarily on economic models. They noted that 'It is increasingly recognized that disciplinary research on agro-ecological and socio-economic issues is not very fruitful'. They concluded that 'bioeconomic models' are an important approach to address the growing mismatch between agro-ecological research focusing on technological options to enhance food security and sustainable land use, and socio-economic research focused on the analysis of production efficiency and the (non-)adoption of technology. The principal purpose of these models is to better assess the impact of economic incentives on the adjustment in agricultural technology choice and land use practices. Bio-economic models represent an interdisciplinary approach that specifies both agro-ecological and behavioural mechanisms and their interactions. These are 'especially suited for analysing the linkages between socio-economic and bio-physical processes at the household level'. According to them, 'bioeconomic' models include: a) econometric specification of consumptive choice and labour allocation, b) discrete definition of technical production coefficients, c) an LP framework for activity choice, d) specific sustainability indicators and d) aggregation through market clearance assumptions.[1] They identified the key areas of improvement needed for bioeconomic modelling as a) relationships between soil erosion and yield, b) dynamics of multiple cropping systems (presumably, nutrient stock-flow concepts), c) better representations of risk and adoption behaviour, multiple market linkages, non-agricultural activities and spatial linkages with other regions. The issue of model scale is also important. There is 'a need for aggregating the results for (representative) households to higher levels of analysis' because economic policies focus on population groups—either at the macro, regional or other aggregate levels—not on individual households. They noted this might be difficult, but also that 'regional models explicitly focusing on aggregating micro-level relations to higher levels of analysis can play an important role in this respect'.

Giller et al. framework on resource use dynamics

Giller et al. (2006) provided another framework emphasizing more sustainable management of soil resources. They discussed the need to 'scale up' analyses of resource use dynamics with a focus on soil degradation processes. A key assertion is that there is a 'lack of integration of available knowledge' and that 'resource management needs to be tackled at the scale of the farming system, including the common lands'. As in Olson et al. (2004), they believed that assessment of the use efficiency and dynamics of natural resources and their interactions requires analysis at a variety of spatial and temporal scales. In response, they described the NUANCES (Nutrient Use in ANimal and Cropping Systems).[2] As a part of this framework, they stated that there must be a 'scaling up' from the field level to the farm level with an 'analytical framework consisting of components in a complete farm system' and that these components can be represented by 'simple summary models'.

They also discussed the need for a broadening of the focus of the analysis beyond agriculture, because 'few farming households in developing countries rely solely for food or well-being on income derived from agricultural production on their own farm'. Thus, 'livelihoods of smallholder

1. This is only one of many possible descriptions of bioeconomic models. As noted above, Kuiper et al. (2001) in the same volume noted the development of 'process-based' complex dynamic systems model that differ in underlying assumptions and methods.
2. This rates low on my listing of creative acronyms, but so be it.

farmers are strongly influenced by opportunities for off-farm [non-agricultural] earnings, through markets for produce and employment' and on remittances. The livelihoods of farm households depend on complex interactions between competing demands for investment of cash and labour. Common lands are valuable as additional resources, but access to these resources is often determined by a 'complex set of local rules'. According to this framework, analyses of crop and livestock production 'cannot ignore the broader political and socio-economic environments in which farming takes place'. They cited Sumberg (2002), who argued that such factors should be accepted as inherent system characteristics when developing technologies and interventions but not as permanent features that determine the agenda for research and development. This suggests that they can be usefully viewed as co-evolutionary. 'Consideration of both socio-economic and agro-ecological conditions allows identification of the windows of opportunity in both time and space that will favour particular forms of management'.

They also emphasized that there are likely to be multiple trajectories 'for a given combination of agro-ecological and socio-economic conditions, a multitude of different combinations' that may be 'equally productive' for farmers. The challenges in this sort of scaling up 'relate to the degree of simplification of processes that is allowed and the site-specific knowledge that is necessary to integrate and move from one scale to the next'. Although a complement to other of the frameworks, there is insufficient detail to allow implementation of this framework very effectively.

Senauer and Venturini food systems globalization framework

Senauer and Venturini (2005) developed a conceptual framework to examine the globalization of the world food system. They classified factors as either 'push' (supply-side), 'pull' (demand-side) or 'enabling' (external). They argued that increasing production of (and trade in) processed foods are largely due to demand-side factors such as increasing desire for variety, high income elasticities of demand for food products of higher quality and greater 'service' components, income growth, urbanization, and lifestyle changes. International migration and the 'communications revolution' have also contributed to the modification of food consumption patterns.

The principal supply-side factors include improvements in food technology, refrigeration technologies and improvements in transportation that have increased food-product tradability. Foreign direct investment (FDI), particularly of the 'horizontal' (market-driven) variety in food manufacturing, has been associated with these effects. In food retailing, 'push' factors such as slow growth in developed country markets and 'pull' factors such as the relative attractiveness of developing country markets have influenced FDI. They identified another 'push' factor as 'the fear of being left behind' by competitors, stating that 'strategic interaction creates strong pressures and incentives to retail internationalization'. Enabling factors include the degree of political instability in a country. Greater stability (and one could add, less corruption) implies greater opportunities for food manufacturers and retailers, and leads to an accelerated process of globalization. This framework operates at a more global level and does not attempt to describe implications for farmers. Reardon et al. (2003) complemented this framework with brief discussion of the implications of supermarket expansions for developing country farmers. However, both these frameworks may be relevant to understand the potential modifications to livestock supply chains and their implications for smallholder producers in a specific country or region.

Colin and Crawford comparison of alternative frameworks for economic analysis of agricultural systems

Colin and Crawford (2000b) described the economic component of research on agricultural systems (noting that the large volume of literature precludes an exhaustive review). They described two 'ideal types' on which agricultural systems research is based: neoclassical micro-economics and heterodox economics. The neoclassical micro-economics approach focuses on 'optimal allocation of scare resources using private markets, with 'efficiency' as the [decision] criterion. The core of this 'paradigm' includes methodological individualism (atomistic decision-makers), rational (full information) choice, stable preferences, no power relationships, focus on equilibrium and commodities and prices as key outcome variables. Applications in agricultural systems include farm management, production economics, and agricultural household economics. The 'heterodox' approach rejects the rational choice model, favouring 'empirical' research focused on 'understanding the actual functioning of the economy and actors' behaviour and institutions, rather than on testing a hypotheoretico-deductive theoretical model'. Applications in agricultural systems work include:

- 'agro-economic studies' (based on non-theoretical economics and with the agricultural system—defined in terms of all relevant social and economic variables—as the object of study)
- 'socio-economic studies' (focusing on the socio-economic organization of production and relying on an institutional methodology but not-exclusively agricultural researchers or institutions, or with an applied, policy-oriented focus
- exploring 'comparative analysis of agricultural systems and their evolution (but typically without formal modelling)'
- generating 'more aggregated qualitative models of the behaviours of types of agents and economic dynamics') and
- 'behavioural-type economic component' of multidisciplinary research with an 'explicit systems-science perspective', and reliance on behavioural economics with regard to adaptive behaviour, lack of perfect information, and rejection of the 'exogenous nature of the objective function'.

This approach suggests that it is important to distinguish between *perceived* and *actual* situations to formulate the decision model. They stated that mathematical programming and econometric or simulation models are 'much less common in action-oriented FSR studies than in knowledge-oriented production economics studies, because FSR researchers tend to eschew the higher degree of abstraction from 'real world' conditions that is believed to be required to apply these methods'.

Fraser et al. panarchy framework for food systems vulnerability

These authors described an approach to assessment of food systems vulnerability, based on the concept of 'panarchy'[3] They noted that 'we have only a poor ability to predict the future of something as complex as the food system' and as a result 'some scholars have moved away from

3. A catchy name, even if it appears to imply that 'everything matters' or is frighteningly close to the word 'anarchy.'

trying to predict the future of global food security, focusing instead on the adaptive capacity of individual communities'. This is consistent with the approach outlined by Döös (2002) above. Fraser et al. (2005) noted that 'this approach has become more common in the climate change literature, where scholars have invested considerable energy into defining resilient communities, social capital and adaptive capacity as a way of identifying regions that may be adversely affected…'. This had led to long lists of variables (social, political, economic and environmental) to evaluate these concepts.

They also stated that a simpler framework based on key indictor variables is necessary, and developed the 'panarchy' concept as a way to conduct 'simple diagnostics of complex systems'. The panarchy framework examines three basic factors:

1) the 'inherent potential of a system that is available for change' (loosely defined as 'wealth' and illustrated for a forest system by 'standing biomass')
2) the 'degree to which a system can control external forces (loosely related to connectedness)[4] and
3) diversity (which is also related to 2) in their thinking because more diverse systems are 'better able to tolerate a wide range of environmental conditions than simple systems.

To apply this concept to the 'food system', they proposed to use 'entitlement theory' based on the assessment by Sen (1980) of strategies used by a community or household to obtain food (direct (production), indirect (purchase), or transfer (gift) entitlements being the three approaches.) They also suggested that the 'pathway approach to connectivity can shed new light on phenomena', and that the focus should be on 'transport media'. Finally, they suggested that portfolio theory could be used to assess diversity and risks. Although they stated that their framework requires the use of 'just three variables' it is more accurate to say that the framework requires consideration of three *categories* of variables, and that the study of the dynamics of transport mechanisms in particular, would be far more complicated in principle than they seem to suggest. Although this framework can be a useful way of structuring thoughts about the future of systems (particularly in the ability of individual communities, households or production systems to respond to change), it is sufficiently non-specific not to be of great value in the present context.

Jakeman and Letcher framework on integrated assessment

Jakeman and Letcher (2003) proposed what they called 'Integrated Assessment' (IA) techniques to deal with the 'many interconnections and complexities within and between the physical and human environment'. They stated that 'it is now possible to assess the effects of resource use and management in an integrated way that provides good guidance for decision making'. The 'discipline' of IA 'has its primary roots in 'global [climate] change impact assessment'. Its characteristics include 'consideration of multiple issues and stakeholders, multiple scales of system representation and behaviour and cascading effects both spatially and temporally'. When the use of models is involved, the models address 'different system components and the incorporation of multiple databases'. They described IA as a problem-focused interdisciplinary activity that uses

4. Connections should probably be expanded to include the types of relationships and their relationship to overall system stability (Nicholson and Fiddaman 2003), but they do not do so.

an interactive approach to enhance communication among stakeholders, links research directly to policy decisions, connects human and natural systems through various forms of spatial and temporal feedback, and focuses on key elements (but also identifies additional information needs through the process).

The development and use of models are major activities of IA, but 'given the complexities of integrated modelling, its broad objective should be to increase understanding of the directions and magnitudes of change under different options. Typically, it should *not be about accepting or treating system outputs as accurate predictions'* (emphasis added). IA analyses should be 'aimed at allowing differentiation between outcomes, at least with a qualitative confidence', which is consistent with the discussion of types of model prediction above. They illustrated the concept of IA for three different water catchment regions, which in the case of a water resource assessment project in northern Thailand included integration of a crop model, a rainfall-runoff model, a sheet erosion model, and an 'economic' model (that was based on short-run maximization of farm profitability).

Constanza et al. complex systems framework for economic ecological analyses

Elements of this framework have been touched on previously in the discussion of model types. These authors suggested that a 'complex systems' approach is useful for modelling interactions between human and natural systems. They defined a 'system' as 'a group of interacting, independent parts linked together by exchanges of energy, matter and information'. 'Complex systems' are characterized by strong (usually nonlinear) interactions between the parts, feedback loops that make it difficult to distinguish cause from effects, delays in spatial and temporal relationships, discontinuities, thresholds and limits. They noted that these characteristics imply that it is usually not appropriate to aggregate small-scale behaviour to arrive at large-scale results (von Bertalanffy 1968). An important distinction is made between classical, 'reductionist' science in which the objective is to dissect the system's elements into smaller isolated parts to reduce the problem to its essential elements and research based on a 'complex systems' approach, which asserts that many systems violate the assumptions necessary for reductionism to work, principally that the interactions and feedbacks between system elements are negligible or that linkages are all linear. As a result, 'achieving a comprehensive understanding that is useful for modelling and prediction of linked ecological economic systems requires the synthesis and integration of several different conceptual frames'. In addition, they believed that 'transdisciplinary collaboration and cooperative synthesis among natural and social scientists' is essential. Definitions of complexity and its implications for economic theory, methods, and policy recommendations are described in more detail in Rosser (1999).

Framework on innovation systems described by Spielman

Spielman (2005) reviewed the literature on what is called the 'Innovation Systems' (IS) approach to agricultural research and technological change. This is related to the objectives of this document because it treats the innovation process explicitly as a part of a larger ongoing dynamic evolution. Given this, the IS framework merits detailed discussion. The IS perspective, although originating in the developed countries (it grew out of literature on evolutionary economics and systems theory),

is being adapted to developing country agricultural technologies. IS 'shifts the emphasis from a unidirectional technology transfer approach to a more complex, process-based systems approach'. This shift in perspective is appropriate for the study of developing country agriculture because it captures the intricate relationships between diverse actors, processes of institutional learning and change, market and non-market institutions, public policy, poverty reduction and socio-economic development'.

An over-arching principle of the IS approach is that 'innovation is a process in which knowledge is accumulated and applied by heterogeneous agents through complex interactions that are conditioned by social and economic institutions'. It emphasizes 'continuous and nonlinear processes of endogenously-determined technological and institutional change' (this from evolutionary economics) and 'the study of the attributes and interactions among diverse elements of a set… and how interdependence among the elements renders the set indivisible and thus analysis of a single element irrelevant' (this from systems theory). According to the IS framework:

- *Innovation* is 'any new knowledge introduced into and utilized in an economic or social process'.
- An *IS* is 'a set of interrelated agents, their interactions, and the institutions that condition their behaviour with respect to the common objective of generating, diffusing and utilizing knowledge or technology'.
- *Agents* are 'individuals or firms, public institutions, non-state actors' who 'enter not as rational maximizers responding to price signals, but as strategists, responding to other agents' behaviours and their institutional context'. There is a long listing of potential agents (p. 13)
- *Types of knowledge* include the scientific/technical, organizational/managerial, codified/explicit, tacit/implicit, embodied vs. disembodied, accessibility and accumulation over time.
- *Sources of knowledge* can be *external* to an agent (he cited journal articles) or *internal* (experiential; not just 'cutting edge' research or public research)
- *Interactions* are relationships among actors (numerous, varied) including spot market exchanges of goods and services that embody new technology, public domain ('costless') acquisition of information, 'durable' (e.g. contractual) agreements, collusive agreements among firms etc. (this essentially ignores social processes like farmer-to-farmer information transfer)
- *Institutions* are laws, regulations, conventions, traditions, norms, routines etc. that condition how agents interact, learn, produce, dissemination and utilized knowledge, and forms of cooperation and competition.
- The *unit of analysis* can be spatial, sector, technological, good or service, temporal.

Spielman (2005) noted (in a markedly understated way): 'In short, a diversity and wealth of analytical dimensions fall within the IS framework'.

One challenge for this sort of analysis, it seems, is to develop appropriate empirical implementations. Spielman (2005) described highly simplistic dynamic game theoretic models in which the proportions of 'innovators' and 'adaptionists' change over time as agents update their behaviour based on learning and feedback processes. Using what is referred to as a 'replicator dynamic' equation, he demonstrated the evolution of the proportion of the two different types of agents, assuming, however that the payoff matrix is exogenous (i.e. independent of the proportion of agents pursuing each strategy). A second set of slightly more complex dynamic game theoretic models include four types of agents (innovators, adaptionists, complementors and imitators). The key findings from the more complex game are that there are multiple equilibria, that payoff structures are important, the 'evolutionary paths' are not necessarily pareto optimal[5] and 'it is difficult to identify conditions for optimality or paths thereto in a dynamic innovation system'. Echoing Rosser (1999), the simple analyses also appear to indicate that 'there is a role for public policy beyond the correction of imperfect markets as identified by neoclassical economics… imperfect institutions', namely, to 'enable an IS to remain flexible and diverse enough to avoid becoming locked into a single trajectory', to 'create incentives for innovative activity', and to 'create institutions that respond to and learn from the innovative process'.

Despite these findings, the game theoretic models ignore (or represent only in the loosest of fashions) the multiple agents, do not allow institutional or incentive evolution, nor deal explicitly with knowledge creation. The key methods used to date under the IS rubric are:

a) descriptive case studies (most frequently), which 'identify institutional constraints and recommend alternative policies, incentive structures or organizational reforms… more often than not, studies are simply *ex post* descriptions of the dynamics and complexities of some technological and institutional innovation;

b) cooperative and non-cooperative game theory (limitations already discussed above);

c) benchmarking (comparative study of the functioning of IS in different countries, mostly applied to the developed countries to date).

At the end of the day, however, Spielman (2005) noted 'there is little evidence to suggest that the application of the innovation systems framework to developing country agriculture is… providing real solutions…. Several methodological and analytical shortcomings are limiting its relevance to the policy and policymaking process…' and 'the link between empirical analysis and policy recommendation remains either nascent or weak in the application of the innovation systems framework to developing country agriculture'. Spielman (2005) attributed the general absence of policy analysis in the IS literature to 'the complexity of the 'systems' approach' and the weakness of its associated methodologies'.[6] His concluding recommendations were that there is a need for more analysis of agents and agent behaviour, the institutions that condition that behaviour and the drivers and interactions that characterize their behaviour. Furthermore, such applications should include more in-depth study of the policy options that may affect the innovative process.

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5. Pareto optimal is used in economics to describe a policy situation in which no individual can be made better off without making at least one other person worse off.
6. This somewhat curious statement suggests that perhaps greater integration of the IS approach with systems-oriented modelling would be fruitful.

A recent CGIAR publication on future directions for research on agriculture (CGIAR Science Council 2005) reiterates some of the themes from Spielman (2005). It noted that 'The continuum from research through to impact is a complex system in which the interactions of many people and organizations continuously throw up possibilities and challenges for new players to address with fresh advances'. In addition, it views the process as driven by technology development and user demand, which results in technological change. Conversely, the development of this continuum is driven by feedback loops and learning processes that enable those involved to respond to emerging needs and circumstances that cannot be predicted. A systems perspective on agricultural innovation 'offers the potential of realizing the promise of science and technology in the context of socio-economic development and merits increased investment in the future'.

Discussion of conceptual frameworks

The previous highly selective set of conceptual (analytical) frameworks underscores two observations. The first is that relatively few authors go beyond description of the elements of their frameworks to delineate the hypothesized causal origins of problem situations, as is appropriate for a true conceptual framework. The second is that there is an incredible diversity of conceptual frameworks that have been developed to address questions of systems evolution. Each of these frameworks tends to emphasize different elements, so it is not surprising that the key variables and concepts are sometimes in conflict. However, there is significant overlap in the frameworks described above,[7] including a) an emphasis on systems approaches, b) the need for better empirical implementation of the general concepts provided, and c) the potential usefulness of both descriptive and mathematical methods. Ultimately, however, an appropriate conceptual framework relevant for analysis of system evolution will depend on the characteristics of the specific system, although it may be appropriate to adapt some of the frameworks above to further develop empirical analyses.

7. With the framework of Boserup probably the least systems-oriented.

Descriptive methods for assessing systems evolution

One approach to predicting systems evolution relies on the development of a detailed description of past events and an interpretive analysis of the reasons why this evolution occurred (usually expressed in terms of certain driving forces). This descriptive *ex post* analysis is then used to make inferences about patterns of future systems evolution, the factors influencing it, and priorities for further study. These descriptive analyses can be related to specific conceptual frameworks, either when a particular framework guides data collection and interpretation or when an objective of the descriptive study is to provide input to develop a conceptual framework (sometimes as a prelude to mathematical modelling). There are notable limits to the types of prediction that descriptive analyses can provide. Predictions based on descriptive analyses tend to be more qualitative than quantitative (e.g. general behavioural modes or trends rather than point prediction).

Obviously, a key step that determines the usefulness of the descriptive analysis is the ability to infer correctly about future behaviours based primarily on the past. If the same sets of relationships are likely to hold in the future, then the past may be a good guide. As noted previously, however, systems that are dynamic and complex have a higher probability of generating unexpected behaviours (or unintended consequences in response to interventions). Thus, descriptive study alone is less likely to accurately predict future behaviours for complex systems. Other limitations of this approach are the inability in most cases to assess alternative possible outcomes through some sort of sensitivity analysis, an often limited number of future variables predicted, difficulty with assessing the impacts of policy and other interventions and the potential lack of analytical or empirical consistency between predicted values of future variables because there is no mathematical framework to ensure it. Descriptive analyses are probably most useful in the organization of information about past behaviours, initial study of underlying cause-and-effect relationships, and as a basis for future empirical model development. A selection of descriptive analyses are used to describe these features and limitations below.

Descriptive analysis examples

Trolladen analysis of systems evolution in the Gambia, 1948–83

Trolladen (1991) developed 'a methodology for studying interacting factors in environmental and agricultural systems in sub-Sahara[n] Africa'. The initial motivation for this is a trend toward decreased food production per capita in the region. Much of the discussion related to defining and measuring the concept of 'carrying capacity'. He noted that the carrying capacity depends on both the current state of society (organization, management, capital and knowledge) and on current natural resources. The concepts of inertia (resistance to change under stress) and resilience (how a system responds to various types of disturbances) are important dimensions of the carrying capacity in ecosystems, and are presumed to apply in the case of agricultural systems also. Trolladen (1991) then discussed 'General Systems Theory' (von Bertalanffy 1968) 'which is built upon the assumption of a hierarchical order with increasing complexity and organization'. 'The systems approach has helped in developing the interfacing of social and economic theory on the one hand, and in physical and biological theory, on the other'. He noted, however, that 'a major obstacle in systems analysis is to define applicable functional subsystems', that 'modelling of complex

systems… require that component parts of the system should be studied… in a functional manner' that is often unfamiliar to many disciplines (including economics and geography), that selecting appropriate boundaries for 'model closure' are often a challenge, and that 'different disciplines have their own ideas of what a system is, along with their own definitions of central questions, scopes and hypotheses'.

He then developed a conceptual model characterized as 'a macro-scale and dynamic modelling system, which emphasizes how the various sub-systems and their interrelationships are functioning. This model is applied to the Gambia from 1948 to 1983. It includes five systems, including:

1) demand (for food, fuel and 'socio-economic development')
2) the economic system (which includes food aid, commercial imports of groundnuts, the current account and groundnut exports as indicator and causal variables)
3) the farming system (with five 'subsystems' including the use of gathered wood for fuel and building, animal husbandry, upland cash crops, upland cereal crops, upland and swamp rice systems), each of which is characterized by flows of matter and energy
4) the 'techno' system (which relates to resource use in the economic and farming systems) and
5) the 'bio' system that relates to vegetation and soil characteristics.

Trolladen (1991) provided a detailed descriptive analysis about the various factors to be included in the model and how they have evolved over time (which is why the analysis mostly falls into the domain of descriptive analysis). Then, key elements of these different systems are linked empirically by 'partial and multiple correlation analysis' that develops correlation values in some detail.[1] Although some of the correlation results are provided, the model is never used for simulation (or if it was, those results are not discussed in the document). Somewhat surprisingly, Trolladen (1991) made few predictions for the future evolution of the system.

Lhoste analysis of livestock systems evolution in Senegal

In a historical review of research on livestock production systems in francophone West Africa, Lhoste (1987) indicated that there had been delays in conceptualization and methodology in developing an approach tied to the historical context and institutions, as well as an insufficient treatment of the multiple relationships between livestock and other agricultural activities. He concluded that what was required was a) better consideration of the complexity of the rural milieu and its dynamic to improve the efficacy of interventions, b) increased reflection about theory and methods appropriate for study objectives in this area and c) the integration of interdisciplinary teams that would include both agricultural and social scientists. Despite these admonitions, subsequent sections of this research report deal almost exclusively with animal science variables associated with the dynamics of extensive cattle production in Senegal. Using secondary and primary data from six herds collected through a 'herd following' approach, he described changes in the numbers, age structure, productivity and weight changes in cattle in extensive systems. This

1. Thus, this work could also be placed into the 'statistical analysis' category. However, the emphasis on describing the past and limited use of the correlation indicators for prediction imply classification as a descriptive study.

basic approach falls within the domain of farming systems research (Norman and Matlon 2000) who described it as a 'notable exception' to the generalization that 'the application of the farming systems approach to livestock enterprises was particularly weak'. Again, few predictions for the future evolution of the system are offered.

Wallis analysis of agricultural intensification and tea development in Kenya

Wallis (1997) reviewed 'eight intensified farming systems most of which have proven effective in exploiting the natural resources upon which they are based, not degrading them but sometimes restoring them'. The emphasis is on 'sustainably intensifying' agricultural production systems. Thus, a part of his underlying conceptual framework concerned a working definition of 'sustainability', which in this case 'refers in the first place to a farming system's physical, chemical and biological elements and how these interact over space and time'. Wallis (1997) adopted the elements of the framework from Norgaard and Dixon (1986) that relates to 'co-evolutionary' methods to assess concurrent changes in physical and social systems. Building upon this approach, he defined four interacting 'subsystems' (market, ecological, social and public) that 'determine whether or not a system has the possibility of being truly sustainable'. He also noted that 'the cases… illustrate that sudden changes in farm productivity may occur when the… domains come into reasonable compatibility.... It is, of course, equally true that an apparently sound and sustainable system may not continue to be sustainable if a major change occurs in any of the… domains'.

According to Wallis (1997), the main driving force for intensification is demand, which in turn depends on farmers having accurate information and 'ready access' to markets for both outputs and inputs. Stability, resilience (ability to withstand and recover from shocks), flexibility, diversity, autonomy and reliability and equity of access to resources are taken to be necessary conditions for the achievement of sustainability. Key factors supporting intensification based on the case studies were: a reasonable degree of law and order in rural area, transportation infrastructure, social infrastructure (health and education; important but the linkages harder to demonstrate), market access (and lack of government monopolization of output markets). Industry-financed research institutes in conducting research more relevant to farmers (as opposed to 'public sector' research organizations, which have demonstrated 'sporadic' progress in the discovery and dissemination of new knowledge and for whom 'the selection of research topics has often lagged behind farmers' real needs') can promote knowledge generation that leads to more effective intensification.

In the chapter on tea development in Kenya, there is a historical discussion of the development of Kenya's tea industry that includes a number of behaviour over time graphs (e.g. tea areas planted, tea production, yields) and related factors (rainfall, country shares of world production, tea prices, organizations of tea producers, development assistance). The document notes in particular the role that the previous experience on tea estates, research from the Tea Research Institute of East Africa, programmes of the Kenya Tea Development Authority (KTDA) and public investment in main and rural roads played in enabling rather rapid expansion of the smallholder tea sector starting in the mid-1960s. As for the future, 'Kenya's tea farming systems are currently viable, but they will have to keep evolving if they are to continue to be sustainable. While they are technically sustainable, they will have to adapt rapidly to continue to be socially and economically sustainable as well'. Wallis (1997) did not predict what sort of adaptation, specifically, is likely to be required.

LUCID working policy brief analysis of land use changes

The analytical framework for the LUCID approach has been discussed previously in Olson et al. (2004). In this short policy brief document, highlights of previous work on transitions (trajectories) in agro-pastoral systems on arid and semi-arid lands (ASAL) are summarized. The document indicated that major trends or issues include competition over access to perennial water, reductions in the economic viability of pastoral systems, land tenure can be a driving force for land use change and the expansion of rainfed and irrigated farming into ASAL. Key findings with regard to water access is that in some areas the conversion of land to crops has slowed as the conversion frontier reaches drought-prone land, that droughts can cause livelihood systems to reach 'tipping points' that result in 'fundamentally different' livelihood strategies being pursued.[2] This is illustrated with a 'time line of significant events' that qualitatively indicated past trajectories of variables from 1930 to 2000. The economic viability of pastoralism has been reduced by decreased access to dry-season water and grazing due to crop farming, establishment of national parks that restrict further access to water and grazing, droughts and civil strife. As a result, some herders have become more sedentary and the species of animals has shifted from cattle to small ruminants (goats and sheep).

The study also indicated that changes in (formal and informal) land tenure have facilitated the increase in cropped land. There is a 'general trend towards land privatization, and fragmentation of former communal holdings' which is affecting access to water, grazing resources and wildlife migration patterns. Rainfed and irrigated farming is expanding into ASAL, in part due to higher returns than to livestock production. In rainfed systems, 'many of the fields are not intensely cultivated. The crops are of low value and risks of drought and pests are high. The cropped land in ASAL is experiencing rapid soil degradation…. Poverty is severe among many of those dependent on rainfed cropping in ASAL', and out-migration for other employment is large. Irrigated lands have high returns, with crops destined to both national and export markets. However, the 'benefits are concentrated in a few hands', and 'impacts… on water quality and quantity are already negative in some areas'. Although focused on examination of past behaviours and the current situation, this short summary provides some limited extrapolations to the future. These include:

- 'With increased individual tenure, the impact of fencing upon livestock management, and upon wildlife dispersal, will increase'
- 'There is evidence that mixed crop–livestock systems [will] promote more sustainable livelihoods through diversification of economic opportunity, and reduced vulnerability to declines in production of one facet of production due to drought, disease or economic forces'
- 'A number of these activities [herding, farming, crop–livestock mix, wildlife-bases] have the potential for value-added through processing of crop and livestock products… that will provide off-farm employment'.

Pingali et al. analysis of agricultural mechanization in SSA

The objective of this well-known study (Pingali et al. 1987; it was also the intellectual precursor of the McIntire et al. (1992) study on crop–livestock integration) was to 'identify the conditions

2. This indicates the importance of nonlinear responses in the evolution of these systems. Presumably, one would want to model what these tipping points are to better understand future behaviours. Work in this area continues under LUCID-affiliated research efforts.

that lead to the transition from hand tools to animal traction and the further transition to the tractor'. To accomplish this objective, however, consideration of the 'context [evolution] of the farming systems' was necessary, because 'the transition from the hand hoe to the plough is closely associated with the intensification of the farming system'. Thus, they expanded the objectives to include the following:

- 'identifying more clearly the conditions under which societies evolve from shifting cultivation to permanent cultivation of land',
- 'analysing the way agroclimatic, soil and infrastructural constraints accelerate[3] or retard this evolution…'.

This study employed an analytical framework based on concepts from Boserup (1965) about intensification being a key driving factor, and the approach of Ruthenberg (1980) to understanding how agro-climatic and soil characteristics influence 'evolutionary trends'.[4] In addition to population growth (land scarcity), the framework also includes the degree of tsetse (trypanosomosis) challenge, soil fertility (yield response to tillage along a toposequence), transportation infrastructure, urbanization, civil strife (ethnic conflicts or slave trade) and land laws and land rights. The conclusions of the study are based on a review of literature, field visits to 50 locations in SSA, synthesis and analysis of data from previous studies, and analysis of data collected during field visits. 'Behaviour over time' graphs from 1930 to 1980 of the number of animal-drawn implements shows rapid growth during the 1960s and 1970s. In their discussion of a framework for assessing the benefits of animal traction, they noted that cross-sectional studies (of adopters and non-adopters; i.e. direct comparisons without econometric controls) will tend to overstate the advantages of draught power because adopting households 'typically differ from households that use the hand hoe in systematic ways that would make those that use animal traction more productive even in the absence of animal draft'.

They proposed that the best approach to studying impacts would be a 'before and after' study, but that the 'next best alternative' is a 'cross-section[al] study with a retrospective element'. A key use of the information reviewed is to discuss 'conceptual issues in the design of animal traction project'. They suggested that 'familiarity with the farming system and its evolution makes it possible' to define characteristics that need to be examined to determine the 'appropriateness' of animal traction in a given region. These include: its profitability (determined by crop-specific factors, market access and transportation infrastructure), access to resources (such as land) and the availability of credit. Thus, the review of evidence of a cross-section of countries does not lead to particular explicit predictions of future outcomes. Rather, it provides to an understanding[5] of the factors that have been important in the past and therefore are presumed to be important in the future.

Soini analysis of land use and livelihood change in Tanzania, 1960–2000

Soini (2005) examined land use change in interactions with livelihoods in a region near Mount Kilimanjaro in Tanzania. The study is motivated by a desire to understand the coping mechanisms

3. One can question how constraints would accelerate evolution.
4. This basic approach has been previously critiqued in Wollmer (1997).
5. In fact, a rather static one given all the history that was reviewed.

and strategies in response to ‘several challenges’ in farming systems that ‘affect local livelihoods’. These challenges include decreasing farm size due to population pressure, which is reputedly ‘limiting the viability of the system’. As a result, farms have become too small to sustain a family ‘under the present management’. Other factors include low coffee prices and global climate change and vegetation change that have affected water supplies. The methods used include aerial photo interpretation (years 1961, 1982 and 2000), ground-truthing for the 2000 map, and a land-use fragmentation analysis. A complementary livelihood study using the sustainable livelihood framework from DFID was carried out in 2001. Forty-five households were interviewed about their livelihood assets, strategies and outcomes, including information on the timing and reasons for introducing or abandoning various activities.

There follows a descriptive summary of the key changes, including the observation that ‘rural livelihoods have become increasingly multi-occupational’ (i.e. both the addition of various agricultural enterprises and non-farm [non-agricultural] activities). One conclusion in this regard is ‘there is clearly plenty of initiative locally, but the locally conceived alternatives are too few and lack integrated approaches of technical agricultural research, economic analysis and policy studies…’. This study did not set out to predict the future, and so spends little time and effort discussing it, but does occasionally offer predictions based on their review of the past 40 years. Soini (2005) noted that the increasing number of households relying on non-agricultural activities ‘will gradually make the area more urban with multiple services being made available in the previously purely agricultural countryside’. This sort of qualitative prediction would have implications for development of agricultural technologies.

Erenstein et al. analysis of integrated rice–vegetable systems in West Africa

One of the more comprehensive descriptive evolution studies is provided by Erenstein et al. (2006). They provided a ‘framework for the analysis of integrated rice–vegetable systems in West African lowlands, built upon the proposition that the benefits of integration can arise to varying degrees along three dimensions: spatial, temporal and management’. The research is developed in part due to ‘indications that participation by small-scale producers is becoming increasingly circumscribed’ in the horticultural sector. In addition, there is explicit mention of ‘evolving views of the dynamics of agricultural intensification’, in particular that along with resource scarcity, intensification can be driven by ‘policy and marketing [market] opportunity’, increasing urbanization, changing food consumption patterns and general economic liberalization being examples of these factors.

Conceptually, integration is in spatial terms as the ‘degree of spatial proximity of the rice and vegetable production activities’ (e.g. in the same plot, on contiguous plots in the same inland valley or irrigated perimeter in the same village etc.). The degree of spatial interaction determines to a large degree the nature of the potential interactions between the rice and vegetable components including biomass transfers, soil nutrient management, modified biological processes. Temporal integration refers to the idea that rice and vegetables can be grown in parallel (intercropping is high integration) or in sequence (rotational cropping gives less integration). Many benefits of temporal integration are related to spatial integration. Management integration recognizes that rice and vegetable production may be managed either by the same person or by different people.

Erenstein et al. (2006) provided a qualitative (tabular) summary of the type and degree of benefits from various types of integration, indicating the degree of integration and the types of effects. They then defined the 'drivers' (factors providing the basic drive for intensification) and 'modifiers' (factors influencing the type and intensity of integration). Although they noted that land scarcity related to population density (i.e. the Boserup hypothesis) 'may be one important factor', they 'consider that marketing opportunity is likely to be the key factor driving rice–vegetable integration'. Market opportunity, they suggested, derives from growth of urban populations, development of transportation infrastructure, and changing food consumption patterns (but does not discuss the origins of these in any detail). Based on this, they hypothesized (predicted) that 'as market access increases, the use of cultivated lowlands will move through a continuum from rice-only, to integrated rice–vegetable, and finally, with very high access to specialized vegetable production systems'. However, this essentially leaves the processes driving evolution of market access unexplained. They also noted that 'this is similar to the relationship between population density and crop–livestock integration discussed by McIntire et al. (1992)' but recognized that there are 'a large number' of modifying factors that will influence this, including agro-ecological zone, storage and handling characteristics of different vegetables and 'the yield and profitability of the rice production system itself'.

They used this framework to provide descriptive analyses of three different rice–vegetable production systems in Ghana, Mali and Côte d'Ivoire that illustrate the diversity of these systems and varying degrees and dimensions of integration (noting also that the degree of integration in these systems is 'partial' at best). The key policy and development implications of their review were:

- Formal irrigation schemes provide a more suitable context for spatially integrated rice–vegetable production, but the relatively high capital, management and labour requirements may restrict opportunities for management integration.
- Integrated rice–vegetable production on the lowlands should probably not be seen as offering significant possibilities in relations to a pro-poor agricultural agenda.
- It will probably be more valuable to develop a better understanding of the range of biophysical and socio-economic factors governing observed patterns of lowland utilization.
- It is not necessarily appropriate to associate integration or integrated systems with poverty alleviation or sustainability.

These conclusions, if re-worded somewhat, can be made more explicit as predictions of future evolution for the system elements they address. However, one lesson from the descriptive studies above is that they are often undertaken without the specific objective of predicting the future than with describing the past. This is not inherently inappropriate, but it suggests that if descriptive studies are to be part of systems evolution studies in the future, care must be taken in their design to ensure that the number and usefulness of predictive inferences are enhanced.

Quantitative methods for assessing systems evolution

In contrast to descriptive methods, quantitative approaches almost always include specific predicted values (or behavioural patterns) for at least some set of variables. That is, although they nearly always share a basis in the past with descriptive analyses, that past focuses on predicting the future. Done well, quantitative approaches have the advantages described in Meadows and Robinson (1985) and discussed above: rigor, comprehensiveness, logic, accessibility and flexibility. This implies that they are potentially quite powerful predictive tools, particularly when based on adequate descriptive studies.

An overwhelming number of basic quantitative approaches and their variants could be applied to assess systems evolution. To keep this task manageable, seven categories of methods have been selected and examples of their application provide an idea of the diversity of their application areas and variants. These eight categories are:

- Statistical analyses (other than time series)
- Time series analyses (distinct from analysis of time series data)
- Dynamic optimization
- Dynamic computable general equilibrium models
- Dynamic partial equilibrium models
- Differential equations-based methods (e.g. system dynamics)
- Agent-based models
- Other simulation approaches (not associated with a particular approach)

It is crucial to note that in many instances, elements of these basic categories are combined in a single model or analysis. For example, Berger (2001) combined a set of (static) optimizing agents into a dynamic agent based model. Wallis et al. (2004) combined agent-based modelling and system dynamics. Many optimization models are based on parameters derived from (often static) statistical analyses, and there is a blurred distinction at times between statistical methods and time series analysis. The combinations are nearly limitless, but to keep things simple, this review will largely discuss applications with a focus on only one approach at a time. In what follows, it will become apparent that certain themes in systems evolution have received more research attention, such as to note that some of the thematic areas where more application of models to future predictions in agricultural systems has been done include: land use change, climate change and soil degradation processes. Thus, many of the examples of empirical applications of the seven methods draw from these areas even if they do not specifically include a livestock component.

Statistical methods

As is the case with many of the other methods that can be used for the prediction of system evolution, there are a plethora of statistical approaches that have been applied in the literature. Particularly for statistical approaches, because they are probably the most commonly applied approach, there is a strong need to be selective about the types of methods to discuss. Prior to

discussion of particular approaches, it is useful to make distinctions (albeit somewhat arbitrary ones) among certain broad categories of statistical approaches. First, it is helpful to distinguish between time-series models (which base predictions primarily on past values of a given variable or system of variables; see discussion below) and what might be termed 'structural' models that use one or more variables other than the one to be predicted as explanatory variables.[1] A second useful distinction among 'structural' models can be made between those models that postulate a specific causal relationship (often derived from theory, especially in economics) and those that seek only to identify correlations among variables (even if based on an underlying conceptual framework). Econometric models tend to be derived from an explicit theory postulated to underlie the data generation process, resulting in greater attention to issues of simultaneity among variables, heteroskedastic error terms (particularly in cross-sectional data), correlated error terms and omitted variables, which will bias either the estimated coefficients or their statistical significance.

A third distinction can be made among models based on their approach to parameter estimation. Although variants of the least-squares approach (ordinary least squares, feasible generalized least squares, two-stage least squares etc.) are still the most commonly used, maximum likelihood techniques, non-parametric estimation and neural networks[2] (Batchelor 1998; StatSoft 2003) have become common in recent years. Different estimation techniques tend to be employed due largely to the assumptions about the nature of the dependent variable (e.g. continuous, discrete, censored) and(or) the error term. A fourth distinction can be made about the spatial nature of the statistical analyses. Many econometric analyses do not have an explicit spatial component, other than that the available data are from a specific (often aggregated) geographic region. Other statistical models are based on spatially-disaggregated data, but a relatively limited number of these models explicitly consider spatial autocorrelation[3] (Griffith 1996).

Given this diversity of approaches to model conceptualization and estimation, it is challenging to generalize about statistical models. An obvious key characteristic of all statistical models is the need for data on the appropriate set of dependent and independent variables. A number of authors (e.g. Berger 2001; Weersink et al. 2004) have noted that this can be a major constraint for the development of policy-relevant agricultural systems models, particularly in developing countries. For example, even at the household level it remains relatively uncommon to see complete econometric estimation of the agricultural household model and often recourse is made to 'reduced-form' models that incorporate a relevant subset of variables assumed to be exogenous (e.g. Nicholson et al. 2004a). Most sector-level and spatial price equilibrium models, even for developed world applications rely on parameters generated from other studies rather than estimating full systems models (Nicholson and Bishop 2004). Discussing household-level

1. This distinction is a bit arbitrary because some time-series models (e.g. ARX models) include additional explanatory variables, and systems of 'structural' equations can include multiple simultaneously determined variables (rendering the distinction between endogenous and exogenous variables more complicated).
2. Many may take issue with this characterization of neural networks as an estimation technique when its philosophical and computational approach differs so greatly from alternatives. This characterization is used here in the limited sense of determining numerical relationships among variables, which at a basic level is what neural networks and more common alternatives do.
3. As an example, one form of a spatially autoregressive model would have the specification $y = \rho Wy + X\beta + \varepsilon$ where y is a vector of spatially-denominated variables, X is a matrix of other explanatory variables, W is a weighting matrix ρ is the spatial autocorrelational parameter, β is a vector of parameters and ε is an error term (Lesschen et al. 2005). It is common not to include the ρWy term even in spatially explicit models, although this omission may be inappropriate depending on the conceptual nature of the spatial correlations (e.g. is one plot of land in forest because it is contiguous to other forest plots, because these contiguous forest plots have other similar characteristics—like distance to an urban centre—or due to both factors?) This issue seems to receive relatively little discussion in many spatial statistical models.

studies, Kruseman (2001) noted that for estimating household-level econometric models of soil degradation 'the data necessary to estimate the equations is difficult to gather… for capturing the effects of soil degradation very long time series are necessary'. Even when the data necessary for a specific study—especially time series data—are made available through specific long-term data collection efforts, this often requires substantial quantities of both time and money. This raises an issue that appears to have been little studied, namely, cost–benefit ratios for generation of the same information (e.g. forecasts) by different modelling approaches.

Despite these challenges, Judge et al. (1988) and numerous other authors have stated that statistical (econometric) models 'have been employed extensively… and have proved to be useful analytic and forecasting tools in practice'. Others, notably Sterman (1991) have concluded the opposite, remarking on the 'well-publicized failure of econometric models[4] to predict the future', which, he caustically added, 'has eroded the credibility of all types of computer models, including those built for very different purposes and using completely different techniques'. Some of Sterman's (1991) criticisms, such as formulation of econometric models on economic theories that assume perfect information, stable equilibria and optimizing agents apply primarily to econometric models based on those assumptions. Other limitations often apply more broadly to many statistical simulation models, including:

1) the neglect of dynamic processes, disequilibrium, and the physical basis for delays between actions and results in model formulation
2) the neglect of 'soft variables' and unmeasured quantities that are acknowledged to be important to determining outcomes due to lack of data
3) the fact that real systems are likely to deviate from the past recorded behaviour, making the historical statistical relationships 'unreliable' as a guide for the necessary (longer-term) time span often relevant for policy analysis.[5]

The third of these points is particularly of concern, and Lesschen et al. (2005) made the rather strong statement that 'statistical approaches do not allow for describing causal relationships'. It is worth noting that economists, e.g. Ethridge (1995), tend to disagree, suggesting that evidence for causality can result from a statistical model based on appropriate (i.e. causal) theory. In practice, most model specifications—and in fact most modelling approaches in general—will likely have difficulty making accurate predictions of the future in the face of structural change. Sterman (2000) noted that models that develop explicit causal structures to include representation of the 'latent dynamics' of a system—even though it may not be currently reflected in statistical relationships—will tend to be more successful in capturing at least qualitative behavioural patterns when structural change is occurring. Additional discussion of the benefits and limitations of statistical approaches will be illustrated through various recent studies using statistical approaches to forecast future system outcomes.

4. Presumably, this refers primarily to macroeconomic forecasting models, but this is not clearly stated.
5. Although numerous econometric studies employ methods to assess 'structural change' in estimated relationships, these analyses are all *ex post*, and therefore provide little guidance about future structural change.

ILRI trajectories of change study

The work on 'trajectories of change' reported in ILRI (2005) has as an explicit goal the analysis of spatially-disaggregated land use change as one element of 'the future evolution of agricultural systems'. More specifically, the overall project objectives were to identify patterns of systems evolution in crop–ruminant livestock systems in Asia and SSA, understand the relationships between 'driving factors' of land use change, develop new methods to predict systems evolution (methods that combine geographic information system, survey techniques and simulation modelling), and identify planning and policy interventions that benefit smallholder producers. The analysis of land use change notes that 'spatial models of land use change are important tools to analyse the possible trajectories of land use change *in the near future*' (emphasis added).

The model developed relies in part on standardized logistic regression models that predict the probability of one of five different farming systems being found at a given location based on socio-economic factors (e.g. population density, market access) and physical factors (e.g. climate, soil properties). This defines what is called the 'supply' of the different farming systems, i.e. what drives the location of the different farming systems on the supply side. The 'demand side' is based on the CLUE-S modelling framework (Verburg et al. 2002), and is used to assess how much land is likely to be needed to produce the amount of four commodities (maize, beans, milk and tea) demanded in the future.

This demand-side analysis for land begins with projections of commodity demands based on 'likely changes in income (GDP/capita) under different scenarios and income elasticities'. Thus, it appears that relatively simplistic trend methods are used to forecast (exogenous) future demand that do not fully account for price responses in local, national or international markets (nor is the source of the GDP per capita forecasts identified). These demand projections are used with information on the amount of each of the commodities provided by each of five farming systems (previously identified via cluster analysis and expert opinion) to 'predict the change in farming systems as driven by the evolution of the demand'. Essentially, this amounts to using an 'iterative procedure' that adjusts the probabilities calculated on the supply side so as to be consistent with the prevalence of the different farming systems needed to supply the demanded quantity of each of the commodities. The authors noted that a limitation of this approach is that 'through this procedure it is possible that the local suitability based on the location factors is overruled by the "iteration variable" due to differences in regional demand'. It is not clearly stated whether the modelled outcomes do, in fact, result in the specified quantities of commodities being produced, nor is it clear how the allocation of production to the different production systems in the future is specified. Thus, the emphasis of this analysis is prediction of how given aggregated indicator variables will be distributed spatially with reasonably high resolution.

Based on the foregoing estimated model, a number of scenarios are developed to examine how the evolution of different exogenous drivers (population density, education, extension services, off-farm employment and market access) influence the spatial pattern of the farming systems in 2024. It appears that any of these variables might be considered endogenously determined with the prevalence of a farming system (i.e. that feedback effects among these and farming system choice could be important), but in this analysis are assumed to be exogenous drivers. Results are

reported for four scenarios: baseline, equitable growth, inequitable growth, and equitable growth with climate change, which derive from alternative assumptions about the values of the exogenous variables (most of which are annual growth rates). Although the report noted that it would be 'interesting to focus on the trajectories of change', in fact, no trajectories over time are presented, only tabular summaries of change from 2004 to 2024. The key results are for changes in the overall prevalence of farming systems, the number and percentage of people deriving income from a particular farming system, the incidence of poverty in different systems (based on 'the assumption that the poverty level varies by farming system and that poverty level decreases over time at the same rate of economic growth'; tenuous assumptions at best).

This analysis pays most attention to the spatial distribution of the farming systems, given certain other estimates of demand for four commodities and changes in other exogenous variables. There are four main concerns with the approach adopted here. First, the 'iterative procedure' used to adjust the probabilities seems *ad hoc*, ignoring the likely feedback effects between spatially oriented supply and demand relationships. Second, the degree of effort put into development of future demand estimates is limited. Because this is a key input into the spatial allocation procedure, it would seem important to devote a greater effort to development of forecasts of commodity demand (i.e. forecasting methods that would account for more than trend analysis of expected GDP growth). Third, except for the spatial allocation of farming systems, all of the key aggregated variables are essentially exogenous. The statistical model essentially provides a transformation of a rather extensive set of exogenous variables into a spatially disaggregated set of farming system locations. Finally, as noted above, if the statistical relationships upon which the allocation model is based evolve over time, the predictions will be less accurate. Verburg et al. (2002) noted that the use of 'empirical relations between land use and driving factors', although 'appropriate for short-term projections if the trend in land-use changes continues… is incapable of projecting changes when the demands for different land-use types change, leading to a discontinuation of the trends'. This comment was directed at statistical land-use modelling work prior to 2002, but it also seems applicable to the methods applied here. Moreover, Lambin et al. (2000), discussing linkages between land use change and land use intensity, noted that 'empirical, statistical models… are only able to predict patterns of land-use changes which are represented in the calibration data set'.

Verburg and van Keulen analysis of livestock and grasslands distribution in China

This analysis has similarities with the trajectories of change work described above (which is not surprising given that one of the principal investigators is involved in both projects). The objective of this research is to 'identify the (proximate) processes that determine the spatial distribution of livestock in China based on a spatial, empirical analysis'. This assessment is motivated by the assertion that 'the unequal distribution of livestock throughout the country will render aggregated assessments at the regional or national levels inadequate for assessing the impacts that changes in livestock numbers can have for certain areas'.[6] The empirical analysis makes use of stepwise regression (variable selection based sequentially adding variables to a linear model that result in the largest marginal explanatory power) based on a data set of 60 'potentially causative' variables

6. Note that this is essentially a 'maintained hypothesis' about the likely degree of aggregation bias for regional or national analyses; it is not tested empirically in this case. Likewise, the usefulness to policymakers of 'pixel level' spatial predictions seems to be little discussed in the literature, whereas regional or subregional aggregations seem intuitively more comprehensible to decision-makers.

to assess the spatial distribution of sheep and goats, 'large animals' pigs and 'draft animals'. Based on this stepwise approach it appears that there is no explicit conceptual framework underlying this analysis. Moreover, some of the 60 variables would be appropriately considered endogenous, such as land use. The analyses are conducted separately for seven different regions of China to account for 'differences in agro-climatic conditions and resource endowments', (presumably in an attempt to control for effects that are not captured directly by the 60 variables), and the significant variables differ by region. A similar (but independent) analysis of the spatial distribution of grasslands is also provided.

Based on the CLUE framework discussed above, Verburg and van Keulen (1999) projected changes in livestock density from 1990 to 2010. They noted that a key assumption of their approach is 'the relations between present land use and the explanatory… variables are… assumed to be constant during the simulation period', which as noted previously, may be a strong assumption. The analysis in the baseline scenario also assumes that 'trade flows for livestock products remain small except for cow milk, so that all increases in consumption are derived from production within China'. The methods to project total livestock product demand and convert it to livestock numbers depend on slaughter weight and off-take rates from Simpson et al. (1994). The potential for increases in sheep, goats and large animals is related to the grassland carrying capacity, but this constraint does not apply to pigs or draught animals. Changes in livestock populations at a given location are driven by (exogenous) changes in the variables identified in the regression analysis, differences between the current livestock population and the predicted value for that location based on the regression models, and 'change in the competitive power between livestock types' due to changes in local conditions or changes in demand.

They reported the spatial distribution of grasslands under a baseline scenario and a 'grassland scenario' in which grassland carrying capacity is increased through grassland restoration, fertilization, more productive species, reduced overgrazing and good rotations. The principal reported outputs with regard to livestock distributions are country-level maps with changes in livestock density from 1990 to 2010 for the four species categories. Because the methods applied here are quite similar to those for the analysis reported above, the limitations are quite similar. The authors also noted, however, that 'the present model does not include an explicit feedback from overgrazing to degradation of grassland into unused land;' rather, the spatial distribution of unused land is based on the statistical relationships. In addition, 'validation of the model results is not possible as the distribution of livestock is only available for one year'. This, and the previous analysis, along with the IMPACT and FAO models in which spatial disaggregation is a priority, suggests that there are tradeoffs in the ability to capture spatial detail vs. other causal processes, often due to data limitations. Combined with the lack of demonstrated aggregation bias, this suggests a complementary role for more spatially-aggregated, but 'process detailed' models.

Overmars and Verburg multi-level analysis of land use change in the Philippines

Overmars and Verburg (2006) developed what they called a 'multilevel' statistical model of land use to assess the probability of land being used for either corn or banana based on data from 151 households in 13 villages in the Philippines. The multilevel approach is based on the idea that land use probabilities may depend on factors at multiple hierarchical levels (e.g. village, household, plot) and that 'both unexplained variation within groups and unexplained variation between

groups is conceived of as random variation and is expressed… as "random effects"'.[7] They noted a number of statistical and practical issues with the use of standard regression models to analyse data generated from hierarchical structures, perhaps most importantly that the use of aggregated higher-level variables (e.g. village-level characteristics to analyse plot-level land use) can result in overestimates of the statistical significance when analysing 'between group differences'.

They developed the set of more-appropriately specified multilevel models based on a logistic regression that include both random and fixed effects for household and village, and compared results for (nested) models with various fixed and random effects. They concluded that multilevel analysis is 'a relevant tool for land use studies because organizational levels and spatial and temporal scale dependencies are characteristic for land use data'. This analysis does not develop specific future projections of land use, but presumably the regression models developed could be used in the same manner as in the studies above to project spatial land use changes. Again, however, the authors stress caution in the application of the approach: 'like any other regression analysis, multilevel models can only reveal associations between variables and partition variance. Additional research is needed to study the causality of the relations'. This underscores that statistical models may be most useful for exploratory analyses, i.e. to suggest future research to further explore statistically important relationships. However, this is not a substitute for developing a better causal understanding of the relationships through other approaches.

Nkonya et al. analysis of nutrient balances in Uganda

Another approach to predicting future outcomes, at least implicitly, with statistical models is developed by Nkonya et al. (2005), who studied the determinants of soil nutrient balances in eastern Uganda. Based on a conceptual framework that stresses the importance of biophysical factors (climate, soil characteristics, topography, altitude, temperature and biodiversity) and socio-economic factors (management practices, crop–livestock integration, household crop sales and purchases, physical assets, human, financial and social capital, the choice of household income-generating activities, land tenure, market access). Unlike many conceptual frameworks, they discussed the likely mechanisms and directions of impacts for these factors. A sample of 58 households was selected for 'an intensive soil fertility study', and data on various biophysical and socio-economic factors were collected. The analysis focused on determinants of 'inflows and outflows that the farmer has control over', i.e. those flows that the farmer cannot significantly influence were not analysed, and the factors influencing the major flows were analysed separately (e.g. separate models are specified for the use of chemical fertilizer and off-farm grazing as ways of influencing nutrient inflows). The authors noted that 'because we are using a small sample, we estimate a "reduced econometric model" in order to have a fair number of degrees of freedom'. In practical terms, this means that only one biophysical factor (agricultural potential, a dummy variable with 1 = low, 0 = high) is used in the analysis. (It also seems to suggest that the authors' recognized that any parameter estimates may be biased due to omitted variables.)

Analyses of net nutrient balances for N, P, K and NPK combined are conducted using the same independent variables (some of which are transformed to log values). Due to heteroskedasticity (commonly observed in cross-sectional data), all the estimated models use Feasible Generalised

7. Thus, there appears to be a significant overlap with fixed and random effects models common in the economics literature.

Least Square (FGLS) ‘to estimate asymptotically efficient parameters’.[8] This analysis is relevant to a discussion of predicting future outcomes because it attempts to relate a dynamic flow concept (nutrient inflows, outflows and balances) to a set of (admittedly static) farm-level characteristics. With some expansion of the sample size and extension of the model to include additional (causal) explanatory factors, the information from this type of analysis could be used to develop more detailed farm-level simulation models.

Time series analysis

Time series analysis[9] (TSA) is a form of statistical analysis that has been used extensively in forecasting future values of variables of interest. In its simplest form, it consists of analytical approaches that use only past values of a variable to predict its future evolution. Thus, TSA departs markedly from the ‘structural’ (i.e. causal or theory-based) formulations of most econometric models. As Judge et al. (1988) noted, it would seem that not employing economic structure in statistical models implies that ‘we neglect information and thus make inefficient use of the data’. However, they stated that because the observed data are not ‘generated by precisely the models economists have provided to explain economic phenomena’ (i.e. all (economic) models are wrong), it ‘should not be surprising that… models that use only the information from a set of observations on a single variable have in some instances provided forecasts that are superior to predictions from a large-scale econometric (structural) model’. For the purposes of prediction, the concept of (inter-temporal) covariance of a ‘stochastic process’[10] is important. If all members of a stochastic process are independent, i.e. the covariance among them is zero, then knowledge of past values will not be helpful in predicting the future.

Time series analysis makes use of four principal model forms. The first is an ‘autoregressive’ (AR) process, in which the random variable y at time t is a function of a certain number of lagged values of previous random variables in the stochastic process. The number of lags p is the ‘order’ of the AR process, and is a focal point for investigation. The second is a ‘moving average’ (MA) process, in which the random variable y at time t is a function of a certain number of lagged previous values of an error term. The number of lags q is the ‘order’ of the MA process and is also a focal point for investigation.[11] ARMA(p,q) models combine these two processes seeking a ‘parsimonious’ representation (i.e. one with fewer parameters to be estimated) of the data-generating process. An ARIMA(p,q) model includes an ‘integrated’, or trend term (whence the ‘I’ in the acronym), which is typically removed via ‘differencing’ sequential values of a series (until it is de-trended, or stationary). A variety of methods can be used to identify the order of the model, but a common one is known as the Box-Jenkins approach. Once the order has been identified and parameters estimated, (conditional) forecasts of future values (conditional on past values) can be made and confidence bounds calculated.

8. Heteroskedasticity implies that ordinary least squares (OLS) regression is still unbiased and consistent, but not efficient in the sense of resulting in lower variance estimates for parameters. Moreover, use of OLS results in biased variance estimates for parameters, and thus biased estimates of statistical significance. Feasible GLS uses sample information to estimate an alternative variance-covariance matrix.
9. This should not be confused with the common use of ‘time-series data’ which can be used to formulate either structural econometric models or various types of ‘time-series models’.
10. A stochastic process is a sequence of observations $y_1, y_2,…y_T$ that are realizations of a sequence of random variables $y_1, y_2,…y_T$ that are part of an infinite such sequence.
11. It is important to note that these two forms are related. It can be shown that any ‘stationary’ AR process (stationary means that the covariance depends only on the distance in time between two members, i.e. that there are no trends) can also be written as an MA process.

Extensions that are common in the economics literature involve the formulation of Vector AR models (VAR), which make use of covariance relationships across multiple variables, ARX models, in which additional vectors of 'exogenous' variables are included, VARMA models in which a VAR model is combined with a vector moving average model, and VARMAX models which include elements of all of these. Note that the ARX and VARMAX models edge back towards structural models through the specification of additional (essentially causal) exogenous variables. An alternative approach is spectral analysis, which is discussed in an application to cattle cycles below. Nerlove and Diebold (1990) noted that 'there is… nothing incompatible with looking at time series as generated by processes of this sort (i.e. ARMA models) and the way spectral analysis looks at them'.

Judge et al. (1988) discussed a number of challenges with time-series models in general and vector time-series models in particular. One issue is determining which of the possible formulations is 'optimal for practical purposes'. This is relevant because a number of possible representations are typically possible, and usually the order of the model must also be estimated from the data. Another issue concerns the 'stationarity' of the underlying stochastic processes. Stationarity is one of the key assumptions 'underlying the asymptotic estimation theory' (i.e. stationarity is required for the estimated order of the process and its parameter values to be reasonably accurate in large samples). They noted that 'many economic time series have trends and regular seasonal components that cannot be captured by a stationary model' and 'transformations of the time series… are not always acceptable'.

In addition to these more statistically oriented concerns, there are practical concerns. First, time-series models require a non-trivial number of past observations to allow estimation of the form and order of the series and to estimate the parameters. For many variables of interest in systems evolution, it is likely that numerical data will be available only for certain periods. Second, even a perfectly specified and estimated time-series model will reflect past (statistical) relationships among variables and will not predict well if the relationships among variables change due to the evolutionary process or policy changes. This is one element of the so-called 'Lucas critique' which suggests that much (econometric) policy analysis based on data generated under one set of policies will not adequately address the likely responses under a new policy regime. A related issue is that it may be difficult to assess the impacts of particular policy changes or factors based on time-series analysis alone given that many policy relevant variables may be excluded from that analysis.

Finkenstädt (1995) described other potential limitations of (linear) time series models, describing fundamentally different views of dynamic (time series) processes:

> There exist two different perspectives to explain this kind of behaviour [time series that exhibit different patterns of qualitative behaviour] within the framework of a dynamical model. The traditional belief is that the time evolution of the series can be explained by a linear dynamical model that is exogenously disturbed by a stochastic process. In that case, the observed irregular behaviour is explained by the influence of external random shocks which do not necessarily have an economic reason. A more recent theory has evolved in economics that attributes the patterns of change in economic time series to an underlying nonlinear structure, which means that fluctuations can as well be caused endogenously by the influence of market forces, preference relations, or technological processes.

He went on to assert that the traditional linear models can only capture a limited number of possible dynamic phenomena (such as convergence to an equilibrium point, steady oscillations, and unbounded divergence), noting that 'If… the underlying structure is assumed to be linear, then the cycle has to be of a symmetric nature'. Economists have become more aware of and interested in nonlinear dynamic models because they can produce a broader variety of possible dynamic outcomes. He also pointed out that in certain types of dynamic systems, use of typical times series analyses may be misleading. Time series that are perfectly related by means of a nonlinear [e.g. chaotic] system, can have a negligibly small correlation coefficient, such that a statistician would refrain from assuming any relationship between these variables, and provides a simple three-equation example. An autocorrelation function (as applied in the Box-Jenkins approach) will work if 'the time series is strictly periodic or converges to a stationary equilibrium', however, 'given a chaotic time series, it might fail to indicate the presence of any relationship'. 'The presence of nonlinearties might shed a different light on the concept of stationarity'. Although there have been many applications of the various forms of time-series analysis in agriculture, a few examples related to yields and prices are reviewed herein to illustrate the application.

Boken analysis of wheat yields in Canada

Boken (2000) used a simplified form of time series analysis to forecast future values of spring wheat yields in provinces of the Canadian prairies. He noted that two different types of forecasts of yield are relevant. 'Long-term' estimates are valuable during October and November (prior to the year in which the crop will be sown) to assist with the 'initial stage' of export planning. 'Short term' forecasts are required close to harvest time, to facilitate the 'final stage' of export planning. Short-term estimates of yield rely on current season weather conditions, information that is obviously not available for the development of long-term estimates. Many long-term forecasts rely on simple trend analysis, and an objective of this research was to determine whether alternative approaches would be more appropriate. He suggested relatively simple techniques (simple moving averages, simple exponential smoothing) for the analysis of series that are stationary, and alternatives (trend analysis, double moving averages and double exponential smoothing) for non-stationary series. Thus, he did not estimate any of the various forms of AR or MA models described above.

These various approaches are tested for the series of average annual wheat yields in Saskatchewan from 1975 to 2003, and comparisons of the mean squared error (MSE) over this period. This sort of analysis is more appropriately applied to a 'forecast period' beyond the period of data used to develop the model, but this was not done in this case because the 'forecast period' included only one-year's observations. Thus, this indicates that even with a time series of nearly 30 years, data can be a limiting factor. The model with the lowest MSE during the period was the 'quadratic trend', but this MSE was only slightly better than the 'linear trend' commonly used for forecasting purposes.

Thraen et al. and Chavas and Kim analyses of US dairy markets

The objectives of the research reported by Thraen et al. (2002) were to develop price forecasting models for the US dairy industry and identify relationships between different dairy prices. They

developed a VAR model using a Bayesian approach.[12] They noted that 'the BVAR model works well when the underlying structure of forces driving the variables is relatively stable'. Somewhat ironically, they previously stated that 'historical relationship between the different [dairy] prices and other economic fundamentals may no longer be valid because the institutional structure of the market has changed'. A 'major advantage' of the VAR approach is stated to be 'that it does not assume any specific structural relationships between the different variables but nonetheless identifies their properties useful for prediction'. The variables in the model include monthly milk and dairy product prices, milk production, and the ratios of dairy product stocks to production during 1988–2001. They derived forecasts for milk and cheese prices for the two-year post-data period through January 2004. These forecasts illustrate two practical limitations of this approach. First, the confidence intervals rather rapidly become quite large, so large in fact that they fall well outside of any historically-observed prices during the previous 14 years. A second (related) limitation is that these confidence intervals do not take into account policies designed to ensure that milk prices remain above specified target levels. To illustrate, the lower bound on the confidence interval reaches USD 0.11/kg when the minimum target price is USD 0.22/kg.

Many of these limitations were addressed by Chavas and Kim (2004) who used similar data series to estimate what amounts to a censored VAR model. Here, 'censored' means that they explicitly recognized that government policies were in place that would place lower bounds on expected prices. Using this approach, they developed models less focused on forecasting than on assessing the dynamic responses to temporary and permanent changes in dairy product prices and the target milk price set by policy. They found that dynamic responses varied under different market conditions (one in which government policy was primarily responsible for prices and one in which market forces determined prices). It is difficult to assess the model's performance (point estimates and confidence intervals) during a 'forecast period' because their analysis was not structured to provide that information.

Mundlak and Huang comparative spectral analysis of livestock cycles

In contrast to the previously-discussed models, Mundlak and Huang (1996) assessed the 'time-series properties' of cattle production in the US, Argentina and Uruguay. Their objective was to highlight the role that differences in technology play in the dynamics of the cattle sector. They employed aggregated country-level data (and the assumptions about aggregate 'technology' that this implies) for four variables: cattle slaughter, price, cow stocks and total herd. They used a relatively simple set of parameters and equations to describe the technology (e.g. stock of cows is unrelated to age distribution of the cattle population, mortality rates equal for all classes of animals, homogeneous maturation ages, fertility rates and mortality rates for all herds, no response of age and weight of slaughtered animals to economic variables). They attempted to estimate the order of the lags in the model, but found that 'the numerical values of the coefficients are inconsistent with our prior guesses' for the values of fertility and mortality rates, due to 'strong multicollinearity among the lagged values of the cow stock'. Thus, they turned to 'non-parametric analysis', where they examined the autocorrelations and the power spectra. After de-trending the series, they

12. Bayesian approaches are based on Bayes' theorem, which states that given an initial probability distribution and a set of observations, 'posterior' probabilities can be calculated. Philosophically, this implies that posterior information is proportional to sample information times prior information, and that probability distributions can be viewed as subjective and individual.

compared the autocorrelations of variables in the three countries and found that these indicate the relative rankings of technology. Their 'spectral analysis' decomposed variations in the data series into different frequencies. They noted that 'a cycle in the data series is simply represented in the frequency domain by a distinctive peak in the spectrum around the frequency that corresponds to the length of the cycle'. They used non-parameteric estimation to estimate the spectra of each of the time series, and found that despite differences in technology, the three countries display 'somewhat similar spectra'. Because of the focus of their work, they did not provide specific forecasts nor confidence intervals.

Dynamic optimization models

Optimization models have long been a mainstay of modelling efforts in agriculture (Hazell and Norton 1986) and there exists an incredibly diverse range of optimization applications (Mayer 2002). In general, optimization models can be characterized by the nature of the objective function to be optimized (e.g. linear, nonlinear, integer, multiple-goal), the nature of the constraints (linear or nonlinear), which tends also to define the nature of the computational algorithm to be employed to find an optimum. The nature of the objective function sometimes relies explicitly on the assumptions of perfect information and optimizing behaviour (e.g. Antle and Stoorvogel 2001) or is sometimes used in a more normative or benchmarking manner (i.e. to indicate what would occur if there were perfect information and optimizing behaviour, and to contrast it with the outcomes of current information and behaviours). Systems-oriented models sometimes use optimization approaches to determine optimal policies or interventions with respect to a set of variables.
In addition, optimization models are sometimes formulated to identify the solutions to market equilibrium problems (e.g. the standard quadratic problem used for most spatial price equilibrium models as developed in Takayama and Judge 1971), although there are alternative problem formulations such as variational inequalities (Nagurney et al. 1996) or mixed complementarity programming (MCP; Nicholson and Bishop 2004) when a market equilibrium problem cannot be formulated explicitly as an optimization model.[13] Most of the optimization models in the literature are static and deterministic.

Kruseman (2001) identified some of the advantages of 'mathematical programming models' (a synonym for optimization models) compared to econometric models, stating that MP models are 'better suited to analyse technology change', due in part to data limitations, but also due to the ability to 'combine economic and biophysical information in an integrated framework'. Approaches such as Nearly Optimal Linear Programming (Jeffrey et al. 1992), by which solutions that are not optimal with respect to any one objective but instead are close to optimal for all objectives, or Goal Programming can be used to address problem situations in which multiple objectives are relevant. Swinton and Black (2000) noted that an area of recent growth is models that link optimization models with 'simulation' (often defined as non-optimizing) models (Berger et al. 2006 is an example).

However, given the objective of predicting the future evolution of an agricultural production system, dynamic optimization models are more appropriate. These models can be multiple-period (with optimization over activities explicitly linked in time or sequence) or dynamic

13. One example of this is when there are discriminatory *ad valorem* tariffs (i.e. differences in percentage tariff rates for a country's different trading partners—a common occurrence) in spatial price equilibrium models.

programming models (in which a suitably-specified set of objective functions and constraints draw upon Bellman's principle of optimality as recently illustrated for farm-level optimization in Tré and Lowenberg-Deboer 2005). However, there appear to be relatively few dynamic models of agricultural systems at scales other than the farm-scale. Although dynamic 'agricultural sector models' have been developed (Hazell and Norton 1986; the WFM and IMPACT are examples) in which multiple products and markets are integrated over time, the number of examples is limited, as described by Deybe (2001). This may be due to attention in this area being diverted to dynamic computable general equilibrium (CGE) models (which would have many similar features but additional macro-economic structure and closure conditions). Hengsdijk and van Ittersum (2002) developed a 'goal oriented' framework land-use systems and implied that dynamic modelling at a spatially disaggregated level can be useful (but they did not explicitly develop such a model).

Although optimization models have been workhorses in the agricultural economics literature, in recent years there appears to be a growing awareness of some of their limitations. Lambin et al. (2000) and Sterman (2000) provided common critiques: the specification of the objective function often is arbitrary, or that underlying behaviour (particularly of individuals, but also of a dynamic system) is not based on optimization. From a more computational point of view, Mayer (2002) summarized some of the characteristics of agricultural systems that can 'cause problems for many of the available optimization techniques' as:

- frequency of functions for which there are no first or second derivatives (which cause problems for optimization algorithms that use gradient methods);
- irregular (non-smooth or convex) response functions, as in 'cliffs and discontinuities when the system is pushed too far';
- size and complexity of the problem space (a useful simulation model of an agricultural system will have 'all of the key variables and pathways of the targeted system', and a correspondingly large number of possible management decisions);
- epistasis (interaction effects) among input options, which may interact strongly but are modelled as independent effects;
- most agricultural systems are in a state of dynamic disequilibrium rather than the equilibrium typically assumed by optimization models. Thus, even if an 'optimal' management pattern (say, for a farm) is developed, the model typically does not provide a transition path based on current individual farm circumstances;
- spatial heterogeneity can imply large aggregation errors if not accounted for properly in the model specification;
- similarly, individual unit variation (e.g. between farms, animals, soils) implies that multiple runs of stochastic simulations and stochastic dominance approaches should be used, but this is infrequently done.

As noted above, in any particular application, the importance of these problems can vary, and can only be adequately evaluated through comparative approaches (which are rarely used). Nonetheless, it is important to recognize that optimization models to assess systems evolution may have one or more of these problems. To address some of these problems, particularly those that relate to the nature of the response function, various authors have proposed alternative

algorithms—collectively termed 'evolutionary algorithms' to determine optimal solutions (Mayer 2002; Mayer et al. 2005). Although the EA may have some desirable properties, work reported by Mayer et al. (2005) seemed to indicate that substantial computing time could be required for convergence to an 'optimal' solution. For an 'individual-animal model' of a beef system, more than one week was required to generate 104 model runs, and it was estimated that 107 runs might be needed 'to give a high probability of finding a global optimum for this model'. It appears that most of the applications of these methods to date have been at the farm level (Mayer 2002), although a non-dynamic spatial model comparing LP and EA approaches has been applied in the Netherlands to 'minimize agricultural nitrogen deposition in nature reserves' (Loonen et al. 2006). Given the literature identified to date, relatively few dynamic optimization models at the level of the 'sector' or 'production system' are discussed herein. One common alternative to models that optimize an objective function is 'rule-based' approaches (Dent et al. 1995). The advantage of rule-based methods lies in their ability to handle qualitative data and uncertainty. According to Dent et al. (1995), when much of the information used in decision-making is in the form of views, opinions and experiences—they imply this is frequently the case in agricultural systems—then a rule-based approach can be quite useful. One example of the contrast between approaches arises in technology adoption processes. As Dent et al. (1995) noted 'Currently this aspect is represented by a profit-maximizing linear program, and as discussed above, this approach is clearly inadequate to reflect the likely dynamics of policy adoption'. In addition, they suggested the greater heterogeneity of farm characteristics and decision rules that are typically incorporated into optimization models that are necessary to 'represent the complexity of social systems' involved.

An implication of the emphasis on rule-based decision-making is that future research must concentrate on understanding the dynamics of the farm household, and in particular on how psychological and cultural variables affect the decision-making process. Others have been critical of the rule-based approach, stating that they are 'limited to a set of predetermined responses to environmental circumstances' (Brown 2000). From an economic perspective, Rosser (1999) noted that 'defenders of the rational expectations approach can be expected to complain that this [rule-based models] will simply lead economists down a slippery slope of adhocracy into a morass of alternative cases and situations among which nobody can reasonably distinguish, the original complaint against adaptive expectations'.

Dhungana et al. model optimizing wheat varietal characteristics

Although not strictly speaking a dynamic model of a production system, the work of Dhungana et al. (2006) is relevant. The objective of this research is to 'develop an approach useful in identifying crop technologies for future conditions'. This work combines the CERES-Wheat simulation model, the HADCM2 climate simulation model and an optimization approach called Response Surface Methodology (RSM) to identify 'optimal combinations of plant traits and management practices that maximise yield'. RSM is 'an optimization approach commonly used in industrial process control and engineering…'. The basic approach involves using the crop simulation model to conduct 'experiments' about how selected genetic traits or management practices influence yields, then estimating linear regressions that provide a 'response surface'. This provides a gradient-type 'path of steepest ascent', and additional simulations following this path are used until yield increases are

minimal. Then another set of 'experiments' is conducted with the simulation model to determine another gradient, and the process is repeated. Thus, this is a type of sequential optimization that is conducted in an iterative fashion with a crop simulation model. A principal contribution of this research is its explicit consideration of what technological characteristics may be optimal in the future, which will allow work to begin on developing wheat varieties with these characteristics now. A major limitation, of course, is the fact that the only factor to be optimized is yield (and higher yields may be decidedly non-optimal in an economic sense, depending on future input and output prices). Moreover, it would seem possible (although likely a significant amount of work) to incorporate the equations of the CERES-Wheat model into an optimization framework directly, which would eliminate the need for the sequential, iterative RSM approach.

Deybe dynamic agricultural sector model for Burkina Faso

Deybe (2001) described the application of the Multilevel Analysis Tool for Agriculture (MATA) to assess the effects of economic policies on farmer welfare, consumer welfare and soil degradation processes in Burkina Faso. The model incorporates the results of crop growth simulation models… within the framework of an economic model designed to represent farmers', herders' and consumers' behaviour at the agricultural sector level. Three interacting modules include a regional optimization model for production that simulates resource allocation decisions in response to expected prices and yields (the latter based on crop simulation models), a partial-equilibrium market model that determines actual [output] prices, and a macro-context module that defines 'general economic variables' that influence farmer and consumer decisions. The model is solved in a stepwise fashion, with production decisions simulated for each region (with random effects of weather on yields), available marketed surpluses (above farm household consumption, presumably) are calculated to estimate 'national market' supply. The partial equilibrium market model is solved to estimate national (urban) prices based on consumers' preferences and budgets, and a current-period net farm price is calculated based on the 'national' price less marketing (transactions costs). These farm prices are used to calculate farm-level income and cash holdings.

The model disaggregates into farm types as characterized by resource allocations, and each farm type is assumed to respond to expected prices in a manner conditioned by type-specific resource constraints. This is one example of an approach that could be used to assess impacts of technologies or policies on the incidence of poverty. In this application, particular attention is paid to the dynamics of soil nutrients, so that yields will be adjusted over time as soil nutrients change. The objective function at the farm level is specified to incorporate risk in two different ways: Target MOTAD (minimization of total absolute deviations) or a utility function including both wealth and its variance. Constant elasticity of substitution food demand functions are derived based on a typology of consumers, and these are used to the market model to determine national prices. The 'macroeconomic context' variables include interest rates, credit available to agriculture, labour demand in the non-agricultural economy, economic growth, incomes; these are specified exogenously. The empirical results reported in this document focus on a five-year time horizon starting in 1994 and assess the impacts of FCFA devaluation, price liberalization and reduced fertilizer availability. Deybe (2001) also noted a number of limitations of the current empirical version of the model, including 'low degree of accuracy of the results on erosion' due

to aggregation of soil types, exclusion of common resource use, and lack of risk-sharing practices known to be common among farmers. He indicated that the latter two factors would require additional disaggregation (to the level of individual farms rather than types and a mechanism (like cellular automata) to represent negotiations between farmers.

Lehtonen et al. dynamic regional sector model for Finland

This study developed a dynamic regional sector model of Finnish agriculture to evaluate the impacts of two policies (restrictions on use of peat soils) to reduce emissions of greenhouse gases on agricultural production and incomes. The conceptual framework they developed is 'a standard economics framework' in which a 'social planner' is assumed to maximize welfare (sector net income) subject to a restriction on the total amount of 'pollution'. Thus, unlike in Deybe (2001), this is not optimization at the farm level, rather, it is the use of optimization to determine a market equilibrium. The empirical model consists of two main parts: 1) a 'technology diffusion' model that determines sector level investments in different production technologies and 2) an optimization model that simulates annual production decisions (i.e. supply) and market-equilibrating prices and demands. The optimization model is similar to a standard spatial price equilibrium model, except that the supply side is represented by what is sometimes termed 'activity analysis' rather than with explicit analytical supply response functions. Agricultural trade activities are included (with differentiation of domestic and imported products, i.e. the Armington assumption). The model uses 17 different production regions for all of Finland. Technical changes and farm-level investments are modelled as a process of technology diffusion based on the profitability, risk and uncertainty of a 'new technique', and the overall savings rate in the economy. Profitability influences the probability of adoption, and it is assumed that farmers do not immediately adopt the most profitable technique due to uncertainty and other 'retardation factors'.

Past investments are assumed to have strong influence on investments. The investment relationships, as in the case of dynamic CGE models (discussed below) are the principal dynamic linkages in the model structure (it appears that demand is held constant). The model is built to reach a steady-state equilibrium in a 10–15 year period given no further policy changes.[14] That is, 'there is a gradual adjustment built-in in the model as fixed production factors and animal biology make immediate adjustments costly'. As is typical in this type of study, the authors compare the results of a 'base' scenario with no changes in climate-related policies (i.e. restrictions on use of peat soils) under various general agricultural policy changes with the outcomes that occur under those same general agricultural policy conditions when restrictions on peat soils are applied. The results show the evolution of agricultural income, cultivated area, CO_2 emissions, and the value of reduced emissions, and cattle stocking densities over the time horizon 1995 to 2020. This type of model integrates a traditional SPE model into a dynamic framework that also attempts to capture biophysical (environmental) effects, and thus may be appropriate for future SE work.

14. Other dynamic models do not assume that a steady-state equilibrium will occur over a given time frame. Moreover, one can question whether the year-to-year market equilibration is appropriate, when other alternative formulations (dynamic disequilibrium models) might indicate different trajectories.

Dynamic CGE models

Another approach that has been applied to examine dynamic impacts on the agricultural sector (and sometimes related environmental outcomes) is dynamic Computable General Equilibrium models (DCGE). These models attempt to capture the general equilibrium (i.e. economy wide) effects of various policy and technological changes. This approach explicitly recognizes that the evolution of the agricultural system and policy impacts 'should preferably be assessed within a macro framework' (Glomsrød 2001), particularly when the agricultural sector constitutes an important component of the overall economy. Static CGE models have been applied at multiple levels including national, regional and even village (Taylor and Adelman 1996). Typically based on what is (somewhat inappropriately) termed a 'social accounting matrix' that describes the structure of inputs and outputs of all (aggregated) goods and services within an economy, a 'core economic model' typically consists of a set of production functions that combine aggregated inputs (land, labour, capital etc.) to produce final outputs. Producers of all goods are assumed to be profit maximizers and consumers are assumed to maximize an analytical utility function. (Thus, CGEs are a form of optimization model.) The equilibrium conditions in all factor and product markets are computed, resulting in prices, incomes, wage rates, and economy-wide savings. Analyses of policies typically are expressed in terms of percentage changes from an initial base scenario.

In dynamic models, the principal dynamic linkage (as in the Lehtonen et al. (2006) partial equilibrium framework described above) is provided by the relationship between savings and capital investment. It is typical to assume a constant specific savings rate, which results in a level of investment in each sector (sometimes specified as a fixed share of the total savings for each sector). This endogenous investment essentially results in a shift in the supply curves for both final and intermediate products, which results in a trajectory over time. When environmental effects (e.g. soil degradation) are included in the model, there will typically be an additional dynamic linkage that relates to soil-related variables (e.g. nutrient balances; Glomsrød 2001) over multiple periods, which will then influence the production functions for agricultural commodities. (In this case, a yield decrease typically would result, which may be partly offset by 'optimal' increases in inputs such as fertilizer.)

Another potential dynamic linkage is labour migration (e.g. from rural to urban areas or from urban areas to an 'agricultural frontier'; Glomsrød 2001) where market imperfections or transactions costs prevent full equilibration of labour markets and thus create a dynamic due to differential returns to labour. The assumption of year-to-year equilibrium need not be invoked, but typically is. Annabi et al. (2005) noted that there is a distinction between what they call 'intertemporal' DCGE models, which are based on 'optimal growth theory' and assume that the behaviour of economic agents is characterized by perfect foresight, and sequential (recursive) models that assume that agents have more 'myopic' behaviour. They asserted that, in general, sequential DCGE models are more appropriate for developing country contexts. Note, however, that Adams et al. (2001) demonstrated that it is possible to formulate a model that allows comparisons of these alternative assumptions.

When DCGE modelling effort focused on a particular sector (product or production system), the level of disaggregation for that sector increases, often to a great degree. This typically implies that the levels of disaggregation for the model differ by sector. One of the main advantages of the

DCGE approach is that it provides for a complete accounting (albeit often at a very aggregated level) of the economic interactions, which can be important when the agricultural sector is a major element of the national economy, or when the research question concerns the impact of various macroeconomic policies on the agricultural sector. Hertel (1992) noted that partial equilibrium models often use 'reduced-form' elasticities of supply that ignore 'gross complementarity' of resources in the agricultural sector, and that partial equilibrium models may often understate the impacts of simultaneous shocks (e.g. oil price increases) to agriculture and other sectors. However, the completeness and theoretical consistency of DCGEs[15] come at a price. Primarily, there must be a sufficient, consistent social accounting matrix available for a given year. Many such SAMs, a modelling framework (Global Trade Analysis Project, GTAP based at Purdue University) and a network of CGE researchers have been developed in recent years. This may lessen the burden on researchers wishing to conduct national-level studies, but this limitation may still apply for the study of specific production systems. In addition, the benefits and needs of a general equilibrium approach for a particular product sector has been questioned. At a basic level, the choice of the GE vs. PE framework comes down to the relevant model characteristics necessary to adequately address the modelling objectives. In situations where the production system to be modelled is a small component of the agricultural economy, where more product or biophysical detail is desired, and where macro-economic policy analysis is not an objective, partial equilibrium models are probably adequate (Nicholson 1996).

Glomsrød DCGE models of Tanzania and Nicaragua

This document summarized two alternative DCGE formulations, both with the essential characteristics of an 'economic core' and an environmental component. One model developed to examine the role of soil degradation in Tanzania included an 'agro-ecological model' that tracks the stock-flow dynamics of soil nitrogen. The representation is relatively simple (five equations) and the farmer decision rules assume that farmers know soil N levels and respond optimally (although they acknowledged that this assumption is 'a crucial question'). The model is used to assess the impacts of a currency devaluation that increases the price of fertilizer. Over 10 years, the principal reported effect is a reduction in fertilizer demand and an increase in the cultivated area. The second DCGE formulation addresses the dynamics of land use change (deforestation) in Nicaragua. As noted above, essential model dynamics concern migration from the 'rural farming' sector to the 'agricultural frontier.' The principal policy question is whether changes in government expenditure and tax policies can slow migration (and deforestation).

Wittwer et al. DCGE model of disease outbreak in the Australian wheat sector

Wittwer et al. (2005) developed a DCGE model to assess the impacts of Karnal bunt[16] incursion in wheat in western Australia. They built upon a regional CGE model (the Monash multi-regional forecasting model) to assess the dynamics of employment and investment in the Australian wheat sector in response to this disease outbreak. They aggregated regions into western Australia and 'Rest

15. However, GE models raise other theoretical issues. According to Kuiper et al. (2001), accounting for price and income effects in a general equilibrium setting has a strong policy implication. 'The Debreu-Mantel-Sonnenschein result showed that aggregating over consumers results in the loss of general properties of the excess demand function (Ginsburgh and Keyzer 1997)'. As a result, no 'generalized predictions' about the effects of economic policies are possible, not even under strict assumptions about [individual] production and consumption behaviour.
16. Karnal bunt, or partial bunt, is a fungal disease of wheat, durum wheat, rye and triticale.

of Australia' based on an already available master database (i.e. SAM). The inputs include labour, capital and materials (but apparently not land), and each industry is assumed to make decisions about input use that 'minimize the costs of producing its output'. The dynamic linkages in the model concern adjustments in tax rates in response to reduced government revenue, adjustments in the labour market (any supply demand gap is closed over time by adjustments in real wages) and investment (which responds to divergences in the ratio of 'actual to required' returns compared to based case forecasts. The base model also includes the possibilities of allowing for technological change, but these are not employed in the subsequent analysis. When used 'in forecasting mode' the model uses exogenous forecasts of macro and trade variables from other models, along with 'trend forecasts' of demographic and consumer-preference variables. This illustrates that for this type of model, some mechanism is needed to generate these additional exogenous variables.

The key assumptions about the initial impacts of the outbreak concerns changes in research and administration costs, increased input use (e.g. sprays) in the wheat production, reduced yields, reductions in wheat quality (which result in lower prices) and quarantine restrictions (which reduce wheat exports from the region). The results describe behaviour from 2004 to 2024 for regional employment, real wages, investment and consumption, the balance of trade, exchange rates, wheat production and value and real incomes. In general, these variables demonstrate patterns of behaviour that differ in the short and long run (e.g. employment initially decreases but then increases to larger than the initial equilibrium quantity). The model indicates that the time required for each of these variables to adjust differs. In general, the maximum effects of all variables are considerably less than 2% different from the initial equilibrium values (by which one may question the need for a GE treatment).

Adams et al. DCGE model of Danish pig production

This research explored the implications of the introduction of a quota for pig production in Denmark under alternative assumptions about the time allowed for adjustment (essentially, immediate, unannounced implementation of the quota vs. previous announcement that allows pre-quota adjustments [they called this gradual implementation of the quota, but this is really a misnomer]). This work uses the Agricultural Applied General Equilibrium (AAGE) model of the Danish economy (inspired, they noted, by the Australian ORANI model). The static version of the model includes 50 industries producing 56 commodities, with land, capital and labour as the primary factors of production in a 'nested CES technology' (i.e. one that includes both intermediate goods and primary factors). Households are assumed to maximize a Stone-Geary utility function. The government sector 'consumes goods, invests in capital, collects taxes, subsidises production, makes transfers to households, accumulates debt, and pays interest'. Export commodities are divided into three groups (traditional exports, non-traditional exports and special exports). All markets are assumed to be competitive except labour, where excess supply can exist.

The key dynamic linkages involve physical capital accumulation, with a one-year delay between investment and operational availability of the capital. Investment in a particular industry responds to the expected rate of return on assets. The model allows for two types of expectation formulation: static or rational expectations. Under the former investors consider only current values to form expectations, whereas under the latter the expected rate of return depends on a net present

value calculation. (It is not explained exactly how this calculation works, because it depends on unknown future values.) Financial asset dynamics arise from government expenditures and receipts and the accumulation of external debt in the private sector due to international trade. Finally, a ‘lagged adjustment process’ using a ‘coefficient of adjustment’ (i.e. a time constant) is used to adjust wage rates in response to various policy shocks. In addition, they modelled the imposition of a quota by ‘exogenizing pig production (assuming a 10% reduction from initial levels) and introducing an endogenous output tax’. The revenues from this tax are transferred to pig producers as personal income.

The model is solved over a 30-year time horizon and the results are presented as deviation from a baseline scenario (they provided limited details on the characteristics of the baseline, but it appears not to be a dynamic equilibrium). The two scenarios analysed assess the immediate imposition of the production quota vs. one that is announced four years prior to its implementation. The results provided are trajectories of pig production, prices, capital and labour use in pig production, national real GDP, wages, employment (changes are less than 0.2% in these variables, again questioning whether a GE approach is needed), capital investment and private consumption. However, changes specific to pig production, such as fertilizer inputs, manure use and primary factor use are larger than changes in the macro-economic aggregates. It is also somewhat intuitive that the evolution of many of these variables is ‘smoother’ when the quota is announced in rather than implemented immediately, however, the announcement alone (under the assumption of rational expectations) causes reductions in pig producer welfare prior to the implementation of the quota due to the fact that adjustments in the pig sector begin at the time of announcement.

Philippidis and Hubbard model of a ban on UK beef exports

Another livestock-industry example is found in Philippidis and Hubbard (2005), who used a DCGE to assess the impacts of a BSE-induced ban on UK beef exports. They noted that comparative static GE analyses ‘are theoretically inconsistent’ because the dynamic behaviour of agents (e.g. dynamic investment decisions of farmers) is overly simplified. The model that is used in this case is a dynamic version of the already-developed GTAP model (version 4, with a benchmark year of 1995 described in greater detail by Ianchovichina and McDougall 2000) for the UK, which incorporated a more complex savings-investment behaviour based on iterative adaptive expectations using annual periods. To implement the ban, they introduced ‘exogenous utility-scaling variables into the Hicksian export-demand functions’ which cause ‘falls in foreign confidence for affected UK meat sectors’ and a corresponding reduction in export demand. They simulated the model over the period 1995 to 2020, comparing a ‘no-ban baseline’ to a variety of export-ban scenarios. They reported tabular results for 1996 (initial response to the ban), 2001 (shortly after the ban was lifted) and 2020 (long-term effects). Three categories of variables (exports, output and trade balances) are reported. Not surprisingly, the impacts on exports are largest (up to 93% reductions in cattle and sheep exports), impacts on output were much more moderate (a 7% reduction in cattle and sheep production in 2001) and essentially no impacts on real UK economic growth (again, questioning the need for a GE modelling approach). Under assumptions of resumed confidence by 2020, reductions from the dynamic baseline are generally small except for cattle and sheep exports.

Annabi et al. DCGE model of poverty dynamics in Senegal

Annabi et al. (2005) developed a DCGE model for Senegal to assess the impacts of trade liberalization on economic growth, income distribution and poverty reduction in Senegal. Thus, this is one of the few models reviewed that can directly address (albeit still at a rather aggregated level), the impacts of interventions on the incidence of poverty. They noted that 'the majority of CGE models used in poverty and inequality analysis are static in nature'. According to them, the inability of this kind of model to account for growth (accumulation) effects makes them inadequate for long-run analysis of the poverty and inequality impacts of economic policies. Similar to most other CGE models, the production technology is a constant elasticity of substitution production function, using a nested structure. In agriculture, the value of production is a function of land and a 'composite factor' (thus, this model does not really focus in detail on the agricultural sector). Labour is assumed to be fully (and presumably immediately) mobile. The dynamic linkages in this model include capital accumulation (i.e. investment, which responds to the rate of return on capital), labour supply growth (based on exogenous population growth), and exogenous 'updating' of transfers and demand for Senegalese exports. This research differs from previous DCGE because it makes extensive use of detailed household surveys that allow the specification of two alternative household types, rural and urban. This allows the development of relationships between the aggregate macro indicators predicted by the 'economic core' of the DCGE model with indicators of impact on households with specific resource allocations (e.g. income sources).

The model 'is formulated as a static model that is solved recursively (sequentially) over a 20 period time horizon' based on a previously-developed 1996 SAM for Senegal. The authors quite appropriately noted that 'in dynamic models the economy grows even without a policy shock and the analysis should be done with respect to the growth path in the absence of any shock'. Thus, they assessed impacts of unilateral trade liberalization as percentage changes from the baseline in 1996 and 2015 (they did not provide specific information about trajectories of change, e.g. behaviour over time graphs). Because the focus of the analysis is income distribution and poverty reduction, they reported results only for aggregated sectors (e.g. 'agriculture' or 'industry'). They found that 'trade liberalization induces small increases in poverty and inequality in the short run as well as contraction in the initially protect agriculture and industrial sectors. In the long run, it enhances capital accumulation, and brings substantial decreases in poverty. However… income distribution worsens, with greater gains among urban dwellers and the non-poor'. A study using a similar DCGE modelling approach for Tunisia (Bibi and Chatti 2006) reached similar conclusions.

Dynamic partial equilibrium models

Partial equilibrium models are often used to examine policy outcomes for a single or related set of markets (Piermartini and Teh 2005). As noted above, a general equilibrium analysis explicitly accounts for all the linkages between sectors of an economy, including households, firms, and governments. CGE models therefore impose constraints on these sectors so that expenditures and incomes for all economic actors are in balance, and thus can be used to determine aggregate income changes in response to various policy options. In contrast, partial equilibrium model usually focuses only on one part or sector of the economy, assuming that the income feedbacks between that sector and the larger economy are small. Partial equilibrium analyses typically focus

on a specific market or product and ignore interactions with other markets. All other factors that can affect this market are assumed to be exogenous or constant (this is the commonly-applied *ceteris paribus* assumption). A partial equilibrium model also does not take into account overall resource constraints in an economy, and thus ignore the need to pull resources away from one sector to increase production in another.

A partial equilibrium model is better suited to policy analysis when a) the policymaker is interested primarily in sectoral policies, b) the sector represents only a small share of total income, or c) policy changes are likely to influence prices in a limited number of markets (Piermartini and Teh 2005). When the agriculture (livestock) sector is a large component of national income, as is more the case for developing countries, a general equilibrium analysis may be more appropriate. Although CGE models often are preferred on theoretical grounds, the benefits of a general equilibrium model can be offset by the high level of aggregation required to be able to use comparable and consistent data and by the difficulties in the specification of parameters and simplified functional forms typically used to represent production and consumption relationships. As noted in Adams et al. (2001) and Wittwer et al. (2005) studies, it is not infrequent for CGE models that focus primarily on one sector to indicate relatively limited general equilibrium (i.e. aggregate income) effects, in which case a partial equilibrium model is likely to be adequate.

A number of dynamic partial equilibrium models have been developed, particularly to analyse changes in international trade policy. These include the Agricultural Trade Policy Simulation Model (ATPSM) developed by UNCTAD, the Static World Policy Simulation Model (SWOPSIM) of the US Department of Agriculture and the SMART model bundled into the World Integrated Trade Solutions (WITS) system. The WFM and IMPACT models reviewed above and the Deybe (2001) agricultural sector (optimization) model are partial equilibrium models. Most partial equilibrium models are solved using optimization routines, so they typically can also be thought of as optimization models. Although a number of dynamic partial equilibrium models have been reviewed previously, three additional model merit discussion: the FAPRI International Livestock and Poultry Model, the AGLINK-COSIMO model from OECD and the ERS/Penn State Trade Model. For the purposes of this section, the focus will be on the livestock components of these models.

FAPRI/CARD International Livestock and Poultry Model

The FAPRI/CARD International Livestock and Poultry Model is a partial equilibrium, econometric, non-spatial policy model. Although the published information is the most limited among the models reviewed in this section,[17] the model structure appears to account for livestock production in somewhat different manner. According to the FAPRI website (www.fapri.org/models/livestock.aspx), 'the structure of the model considers carefully the biological processes involved in livestock and meat production' and 'captures the investment, production, and consumption decisions of significant economic agents'. In particular, the FAPRI model appears to make explicit delineation between stock and flow variables, allowing changes in stocks (e.g. animal inventories) only through 'flow variables' (e.g. slaughter). These flow variables are the relevant ones for the specification of economic decisions. Consistent with the previous concepts

17. Communication with Jacinto Fabiosa from FAPRI indicated that no detailed model description document is publicly available at this time.

the flow variables are specified in terms of rates rather than levels. According to FAPRI 'Rates normally give a more stable behaviour to the model compared with levels and lend easily to comparison across countries and time periods'.

In general, the demand side of the FAPRI model is driven by prices, income, and population, whereas the supply side responds to prices, costs of production, and technology. Although often expressed as a residual, livestock trade is sometimes a function of domestic price relative to the world price. As in the case of the other models, prices in individual countries are determined either through price transmission from the world price when trade is relatively free, and through market clearing when there are significant restrictions in trade flow. The overall model solves for a market-clearing world price that balances world trade and equates supply and demand in individual countries. Parameters in the model are directly estimated, from the literature, or the consensus. The model includes key policy instruments that influence the incentives faced by livestock producers and consumers, including domestic policies (e.g. price support) and border policies (e.g. duties, tariff rate quotas, export subsidies). As the available documentation notes, 'other policies that are difficult to represent quantitatively, such as environmental regulations, are accounted for exogenously'.

AGLINK/COSIMO model

The AGLINK/COSIMO model is, in a sense, the successor to the WFM. Development of the AGLINK model was begun in the early 1990s and in 2004, the OECD and FAO agreed to collaborate on the extension of the AGLINK model to a larger number of developing countries and regions. Practically, this has meant the development of new country and region 'modules' that can be selectively integrated into the AGLINK framework. AGLINK is a dynamic partial equilibrium model of world agriculture. It simulates annual supply, demand and prices for grains (wheat, course grains, rice) oilseeds and oilseed meals, vegetable oils, milk and dairy products, and livestock products (beef and veal, pigmeat, poultry meat, sheep meat and eggs). Certain markets, such as butter oil, concentrated milk, cotton, lamb, roots and tubers, fish and wool are 'modelled incompletely', and the OECD document notes rather cryptically that 'this may affect the interpretation of model properties'. The AGLINK component of the model consists of endogenous modules for eight OECD countries/regions and four non-OECD countries. The eight OECD countries (OECD-8) are Australia, Canada, European Union (25), Japan, Korea, Mexico, New Zealand and the United States. The four non-OECD countries are Argentina, Brazil, China and Russia.

A principal purpose of the model is analysis of the impacts of agricultural and trade policies on agricultural markets in the medium-term. The model assumes that all markets are perfectly competitive and that domestic and imported products are viewed as perfect substitutes by consumers. The nature of linkages between AGLINK and COSIMO modules depends on the specific commodity. For cereals, oilseeds and dairy products, there is interaction between all endogenous AGLINK and COSIMO modules. For red meats, AGLINK-COSIMO specifies three markets by Foot and Mouth disease status: the disease free Pacific beef market, the Atlantic beef market and all other areas of the world are included in the residual FMD beef market. Pigmeat markets are similarly segmented. AGLINK makes a distinction between livestock slaughter that

takes place in slaughterhouses and indigenous production, although how this influences model outcomes is not discussed. Trade is specified in one of three ways: exogenously when there is a trade quota or access agreement,[18] bilaterally for poultry trade between the US and Canada, and most commonly as a residual obtained from the summation of domestic supply and utilization balances. The documentation notes that in the ultimate case 'it is the responsibility of the market analyst to identify cases where simulated exports are above export limits or where simulated imports are below import access'.

The AGLINK-COSIMO model appears to pay more attention than most other models to treatment of feed demand for livestock. Price-responsive expenditures on individual feeds and a variable feed share are used to develop a feed cost index. This index is one factor affecting livestock production. The adjustment of feed demand to a change in feed price responds to both relative prices (the share of each feed) and overall feed demand. Given the available information, it is not known how nutrients from forage are treated in the model, nor how the feed requirements are specified (e.g. per animal or per unit production). As noted for the DCGE models, a key component of the dynamics is investment decisions over time. In AGLINK, the investment demand equations for beef cows are a function of expected producer prices, feed costs and 'other factors'. The beef production equations link supply in a given year to the breeding inventories in earlier years, to producer prices for beef, to costs and 'in some cases' to lagged prices for competing products.

The pork supply equations make annual production a function of lagged production, producer prices and feed costs with lags up to three periods. A complete revision of the representation of poultry markets was underway in 2006. For most countries, it is assumed that poultry and eggs are 'constant cost' industries, that is, that their price is assumed to be determined completely by costs. Quantities are given as sum of endogenous domestic demand, and exogenous net trade. Demand for meat and eggs are functions of deflated farm prices, per capita consumer incomes and population. For some countries, meat demand is influenced by prices of fish or crop products.

In contrast to many other model description documents reviewed herein, the documentation for the AGLINK-COSIMO model includes a number of model evaluation exercises. The document notes that:

> Beyond the primary objective of deriving a baseline solution, a main concern for any dynamic model is the stability of the solution in the face of rational exogenous shocks. More specifically, the question is whether the equilibrium solution is unique to a set of values of the exogenous variables and furthermore, how quickly does the model return to that equilibrium solution after being subjected to shocks to a subset of the exogenous variables, if at all?[19]

18. The presence of a trade quota or access agreement, however, does not imply that the quota will be filled, as shown by Nicholson (2002) for US dairy product imports.
19. The section on system dynamics models below notes that this emphasis on whether a model attains a stable equilibrium is not shared by all modelling approaches.

To evaluate this, a set of 'stability simulations' are performed in which all exogenous variables are made constant over 20 years at their 2005 values, and the behaviour of percentage price changes are examined. The behaviours of particular interest are whether price changes dampen, the amplitude and period of price oscillations, and the length of time the model requires for price fluctuation to become minimal. In general, the stability simulations suggest reasonable model behaviour. In addition, the model was tested to examine whether a 1% increase in GDP for all countries produced qualitatively reasonable outcomes (e.g. larger increases in demand for commodities with higher income elasticities). Finally, the documentation includes some discussion of the usefulness of including stochastic elements for yields and GDP growth in the model, rather than using it to provide only one deterministic solution path.

ERS/Penn State trade model

The ERS/Penn State trade model is the most completely documented of the models reviewed in this section. Like the others, it is an applied partial equilibrium, multiple-commodity, multiple-region (but non-spatial)[20] model of agricultural policy and international agricultural trade. As its name suggests, it was developed by ERS with the collaboration of Penn State University for analysing trade policy. The model attempts to 'build on best practices in previous agricultural trade models while at the same time incorporating a much wider range of domestic and border policies than most previous models'. The current model version includes 12 countries or regions chosen based on their interest to the agricultural situation of the United States: the United States, European Union (EU-15), Japan, Canada, Mexico, Brazil, Argentina, China, Australia, New Zealand, South Korea, and the Rest of the World (ROW). Thirty-five agricultural commodities are specified in the model: 13 crops (rice, wheat, corn, other coarse grains, soybeans, sunflower seed, rapeseed, peanuts, cotton (both as a fibre and oilseed), other oilseeds, tropical oils, and sugar), 12 oilseed products (soybean oil and meal, sunflower seed oil and meal, rapeseed oil and meal, cottonseed oil and meal, peanut oil and meal, other oilseed oil and meal), four livestock products (beef and veal, pork, poultry, raw milk), and 6 processed dairy products (fluid milk, butter, cheese, nonfat dry milk, whole dry milk, and other dairy products). Raw milk, fluid milk, and other dairy products are non-traded commodities. Consumers are assumed to view domestic and imported products as perfect substitutes (Stout and Abler 2004).

The model includes a broad range of trade policies (specific and *ad valorem* import and export taxes/subsidies, tariff-rate quotas) and domestic agricultural policies (e.g. producer and consumer subsidies, production quotas). The inclusion of these policies may be facilitated by the use of a mixed complementarity programming approach (MCP; Bishop 2004), but this is hinted at only through the manner in which the model results are computed (Stout and Abler 2004, 3). The model uses USDA data on area, yield, production, consumption, stocks, and trade from the Production, Supply and Distribution (PS&D) database for a 2000 base year. Unlike other models discussed in this document, the ERS/Penn State model can be run either as a comparative static model or as a dynamic model. For the latter type of analysis, the model is solved sequentially for a sequence of years. There is also an option to use Nerlovian partial adjustment factors, which make the short-term responses in crop production, livestock production, and dairy processing. Parameters are from the literature and from other trade models (including AGLINK, WFM and IMPACT).

20. That is, it is a gross trade model that does not predict specific trade flows among countries or regions.

Livestock production is a function of the previous period's production, a feed cost index, producer prices for livestock products and an arbitrary scaling factor so that model-calculated production in the base year equals observed production. Although probably similar to the AGLINK specification, this differs from the FAPRI specification in which animal numbers and offtake are modelled explicitly as stock-flow concepts. The feed cost index is essentially a weighted average feed cost in which feed shares are constant but feed prices vary. Feed demands are specified for each of the four livestock products in the model, and commodities used as feed are the grains and oilseed meals (again, forage resources apparently are ignored). Feed demands are function of current production (again, rather than as a function of the current animal *population*) feed prices, and an arbitrary scaling factor so that model-calculated feed demand in the base year equals the observed value. Demand for livestock products is modelled as a function of prices and an arbitrary scaling factor so that model-calculated demand in the base year equals observed demand.

Differential equations modelling (system dynamics)

Models based on systems of differential equations (often nonlinear) are common in many disciplines (engineering, ecology, even economics). However, different names are applied to them and the underlying conceptual and philosophical frameworks can be quite different. Without trying to commit any injustice against other approaches based on differential equations, the focus herein will be on what are called 'system dynamics'(SD) models.[21] System dynamics provides a set of conceptual tools to understand the structure and dynamics of complex systems. In this sense, it has much in common with the conceptual approaches to the study of 'complex systems' (e.g. 'evolutionary approaches' as discussed by Costanza et al. 1993), systems ecology (e.g. Kitching 1983) and to the other approaches that stress systematic thinking (e.g. Colin and Crawford 2000b; Norman and Matlon 2000). It also encompasses a modelling method that facilitates the development of simulation models of complex systems and their use to design more effective technologies and policies. A key element, of course, is the emphasis on inter-temporal change. In practical terms, SD can be viewed as the application of systems engineering concepts to social and economic systems. Thus, SD models are typically formulated as systems of ordinary differential equations because of their complexity (and sometimes nonlinearity) are typically solved by numerical integration rather than by analytical methods. Numerical integration is the iterative calculation of the values of state (stock) variables and rate (flow) variables given a set of starting values.

Although the use of systems of differential equations and numerical integration is not new, the SD perspective on the use of these mathematical tools distinguishes it from other approaches. Some of the key elements of the SD perspective are:

1) Focusing on 'dynamic complexity' (an example would be when short- and long-term outcomes of an intervention differ due to feedback processes) rather than 'detail complexity' (in which a great deal of spatial or other disaggregation is emphasized);

21. This is in part because I am most familiar with these models, but I also believe that the modelling approach and philosophy is consistent with many of the characteristics of modelling problems in agricultural development. Note that the use of the singular 'system' implies that only one system is under consideration in a given modelling effort. However, this is a bit of a misnomer, because the emphasis is typically on improving understanding of a particular 'problem behaviour' over time (and what can be done about it), so some have suggested the SD should be re-christened 'Problem Dynamics'.

2) Adopting an 'endogenous perspective', which asserts that 'the persistent dynamic tendencies of any complex system arise from its internal causal structure' (Meadows and Robinson 1985) rather than from external shocks. This results in a tendency to avoid the use of strictly exogenous explanations (as occurs in some statistical models e.g. Verburg et al. 2002);

3) Emphasizing on explicit characterization of a system in terms of its stocks, flows and feedback processes, which are considered essential elements of the causal structure underlying all dynamic behaviours. SD models are based on what are hypothesized to be the underlying causal relationships, not on observed statistical correlations among system variables;

4) Focusing on 'general dynamic tendencies' rather than forecasts of point values at specific future dates (although some SD models are explicitly used for point forecasts).[22] 'General dynamic tendencies' include the conditions under which the system is stable or unstable, growing, declining, self-correcting or in equilibrium.

5) Emphasizing on disequilibrium processes, rather than equilibrium assumptions. That is, SD models almost never assume (impose) that a system's natural tendency is toward a stable equilibrium. A corollary is that the trajectory of changes and their fundamental mode of behaviour are important considerations;

6) Employing broader variable and data definitions. SD modellers tend to be willing to incorporate variables for which no explicit data are available, either for quantities that could in principle be quantified and collected, or for more conceptual variables. For example, 'soft' variables such as 'goals, perceptions, and expectations' are often included—even if more difficult to measure—if they are believed important to understanding the behaviour of the system. SD modellers assume that if a variable is important conceptually, it should be modelled even if no numerical data are available, because to omit the variable is to assume the impact is zero (which is logically inconsistent with its conceptual importance).[23]

7) Using behavioural assumptions derived from behavioural psychology or key informants (decision-makers) rather than those from economic theory (although there are also numerous exceptions to this). This has much in common with 'rule-based' approaches to decision-making although these latter are typically structured as 'if–then statements' as in many empirical rule-based models.

8) Developing approaches to explicitly include various decision-makers and stakeholders in the process of model building, evaluation and use (e.g. Vennix 1996).

SD models have been widely applied to problems in business (Sterman 2000) and environmental issues (Ford 1999), but appear to have been less applied to agricultural systems and international development. One reason for this appearance, however, seems to be that relatively few researchers using SD-like methods apply the term 'system dynamics' to their work, even if they explicitly cited

22. One reason for the lack of emphasis on point predictions is the fact that in dynamic systems that are sensitive to random perturbations, even perfect knowledge of the causal structure and parameters can lead to models being essentially of no use for point prediction beyond a certain time horizon (Sterman 2000, 877–878).

23. Döös (2002) adopted an alternative perspective that suggests in the absence of sufficient information, inclusion of an element in a simulation model can lead to erroneous conclusions. Essentially, this is a debate over whether it is appropriate to have 'no information' or 'incorrect information' in a model structure.

SD reference works in the course of model discussion. Thus in Bontkes (1999, 2001; discussed below), reference is made to a 'process-based' model.[24] The farm-level GRAZE model (Loewer 1998) referred rather generically to 'a dynamic simulation model', and Rosser (1999) lumped SD into the general category of 'cybernetics' in discussions of dynamic economic models, and other authors essentially adopted an SD perspective described as 'rule-based'.

However, there are a limited number of production-system models and international development models based on SD. One of the first agricultural issues to be addressed with SD was the origins of price and output cycles in hog production in the US (Meadows 1970). More recently, Saeed (1994) has explored basic development policy options, but at a national level. Kassa et al. (2002) and Nicholson et al. (2003) developed frameworks for livelihood systems in the Ethiopian highlands and the linkages between dairy cow ownership and child nutrition in Kenya, respectively, using SD concepts and diagrams, but no formal simulation models. Newman et al. (2003) developed an empirical SD model of malaria control in Bolivia as a monitoring and evaluation exercise for the World Bank. In an attempt to illustrate the potential usefulness of SD modelling in the context of evolving agricultural systems, four examples of empirical SD models that provide insights into such situations are discussed herein. Although the examples are diverse, none directly addresses the question of how to design better technological and policy options in specific agricultural systems in the developing world.

Various forms of SD models (whether explicitly called that or not) have been criticized by numerous authors. Rosser (1999), in his discussion of models of complex economic dynamics, provided glib criticisms ('dubious recommendations' from a 'questionable model') of work on the evolution of urban areas in Forrester (1969). Lambin et al. (2000) criticized 'process-based' models of land-cover changes because 'they condense and aggregate complex ecosystems into a small number of differential equations in a stylized manner' and stated that 'the scale issue is difficult to deal with in dynamic simulation models' because locally-observed decision rules cannot be used to model aggregate behaviour. These criticisms would seem to be more directly applicable to the manner in which specific models were implemented, rather than as a broadly acceptable criticism of the approach. It is also necessary to keep in mind the purpose of a particular modelling effort, matching criticism of the model to its stated purpose (and this is not always done). The use of a high degree of aggregation that tend to be a hallmark of SD has been criticized as having 'little foundation' compared to the use of 'local relationships among individual actors' in which aggregate behaviours or structures 'emerge' out of self-organization rather than being imposed or assumed (Rosser 1999).

Meadows et al. limits to growth model

This study was commissioned in the early 1970s by the Club of Rome to address five major trends of global concern: accelerating industrialization, rapid population growth, widespread malnutrition, depletion of non-renewable resources and deterioration of environmental quality (Meadows et al. 1972). In the first model formulation, the emphasis was on broad modes of

24. The term 'process' often refers to the use of continuous response functions to simulate production and other outcomes rather than a discrete set of input–output combinations.

behaviour based on the interactions among the human population and non-renewable resources. The model structure included three main stocks: an aggregated human population, an aggregated non-renewable resource, and an aggregated stock of long-lived pollutants. The authors noted that this has the advantage of making the model more understandable, but the (perhaps large) disadvantage of placing significant limits on the information that the modelling exercise can provide. The model predicted that the world system was likely to demonstrate a behaviour known as 'overshoot and collapse', that is, that the current world system was not sustainable. Moreover, an increase in the amount of the non-renewable resource available only postponed, but did not prevent, this collapse. Moreover, a set of alternative and more optimistic conclusions about technology (energy supplies, pollution control, birth control and agricultural yields) still led to cessation of (economic) growth by 2100. They ultimately argued that population control and limits on capital investment are necessary to reach a sustainable dynamic equilibrium for the world system. Many subsequent authors have been critical of the methods, specific model assumptions and conclusions of this study. It is included in this review not because of its specific conclusions, but because it illustrates the application of SD modelling to predict the evolution of an important (in fact, all-encompassing) socio-economic system.

Bontkes model of agricultural production systems in Mali

The modelling work of Bontkes (1999, 2001) described an approach that is 'suitable to provide a qualitative insight in[to] the dynamics of agricultural development'. For the Koutiala region of sourthern Mali, a dynamic model simulates the evolution of outcomes for four farm types over the period 1980–2025. The focus of the model was on interventions that policymakers should take to prevent further soil degradation. The model included an extensive biophysical representation with three soil types, food (maize, millet) and cash crops (cotton, groundnut), cattle production (and related feed quantity and quality variables), and nutrient cycling. Allocation decisions (e.g. land planted, animals sold are purchased) are based on food requirements, food preferences (e.g. millet vs. maize), expected yields, and 'economic surpluses' per crop over the last three years, and cash stocks. This type of decision model is consistent with the 'adaptive' or 'extrapolative' expectations formulations often used in SD models, in which decision-makers use available information (i.e. not perfect information) and decision heuristics, rather than optimizing. Bontkes (1999, 2001) noted that 'an advantage of the use of decision rules is that they allow more flexibility in the modelling of decision processes by taking into account a large variety of considerations'. Decision rules are also relatively easy to validate with stakeholders, but, he noted, 'may change under changing circumstances'. In addition to modelling biophysical and socio-economic processes at the farm level, Bontkes (1999, 2001) included a mechanism to aggregate farms from the four categories. The model allowed for endogenous switching among the categories based on farm-level dynamics, and hence provided predictions of the number of farms in each category over time as the system evolves. These aggregations of farm numbers are matched with simple market models of demand growth, which allow regional prices to be determined as a model output rather than as exogenous variables. A similar farm-to-region aggregation strategy was employed by Pagel (2005) in an SD model assessing the impact of agricultural policies on farm-level structural change in the US dairy sector.

Baseline simulations show the trajectory of soil organic matter, grain yields, and herd size until 2025. Policy experiments involving discrete shocks to the price of cotton and fertilizer are used

to explore changes in the area of cotton planted. Bontkes described some of the limitations of his model as arising ‘due to the lack of tested theories’, particularly of the rule-based decision structure, and the ‘paucity of reliable longitudinal data that are required to construct and validate’ the model. However, he also suggested that his model could be useful ‘to improve understanding of the dynamics of the system allowing decision-makers to improve the quality of their decisions. The model may help to discover discontinuities in behaviour when conditions change’ and ‘identification of topics for agricultural research’. Moreover, he noted that it is possible to include stakeholders in the model-building process, in which case the model can serve as a consensus-building exercise, ‘building mutual understanding and maintain[ing] a meaningful dialogue’ between groups.

Qu and Barney China grain sector model

Qu and Barney (1999) developed an SD model (based in part on seven other previously-developed models) to make projections of grain production and consumption in China during the period 1980 to 2020. The model included six regions, four grains, and nine livestock products. Thus, this is a dynamic, regionally disaggregated, partial equilibrium, multiple-market model. Grain production is the product of yield and harvested area. Yield is modelled as a function of investments in irrigation and agricultural research, producer prices, other input prices, water availability and [aggregated] soil quality. Harvested area is determined by the amount of land cultivated, a cropping intensity index (which related cropped land to harvested land) and expected producer prices (using adaptive expectations). Grain demands are determined by overall growth in food demand, expenditure shares of each grain, and consumer grain prices, and a similar mechanism is used to calculate meat demand. Feed requirements for livestock are calculated based on meat production (assumed to be equal to the difference between meat consumption and imports), the proportion of animals of each type fed grain and species-specific feed-to-meat conversion ratios. In contrast to many SD-based market models, grain prices are assumed to be exogenous (given that projections of real world grain prices are ‘flat or declining’ and the assumption that ‘domestic real prices for grain will have a similar trend’). Thus, this model appears to ignore a number of potentially relevant feedback processes. The authors cited the following as strengths of their model: it builds upon previous more detailed modelling efforts from USDA and other organizations, it is transparent (i.e. well-documented and available to others for use), and it is has been tested (primarily through assessment of its ability to predict actual outcomes in China’s grain markets during 1980–98). The authors presented comparisons of their model projections with those from USDA, finding that the two models predict similar outcomes for the baseline scenario. They then applied the model to assess the impacts of limited ‘land loss’ (presumably, land degradation severe enough that the land is abandoned), greater investment in agricultural research, higher GDP growth, increases in allowable meat imports, and various combinations. They noted that the model could be improved to better deal with the dual state-market nature of price formation, water availability issues, the relationship between investments in agricultural research and grain yields, the costs and complexities of the various implemented policy scenarios, inconsistencies in reported data (especially area harvested), and grain stocks variables to allow assessment of short-term food security.

Millennium Institute model of development policies and outcomes in Mozambique

The Millennium Institute (2005) described what they viewed as a set of 'new standards for development models' based on the principles outlined in the Comprehensive Development Framework and the specification of the Millennium Development Goals (MDGs). These standards include the ability of models to address the interdependence of multiple development processes, provide a holistic, long-term development strategy, assure broad country-specific ownership and direction of the development agenda, facilitate strong partnerships among domestic and international stakeholders, and focus on results and practical successes. The model developed for Mozambique, they asserted, meets most of these (admittedly ambitious) standards. The Threshold 21 (for 'threshold of the 21st century') model is 'a quantitative tool for integrated, comprehensive development analysis'. Its purpose is to support the overall process of development planning by facilitating information collection and organization and analysis of alternative development strategies.

The model consists of several interacting 'core' modules. The economic core includes aggregated agriculture, industry, service and government sectors (it appears to share many characteristics with many (static) CGE models, including an underlying basis in a SAM; the key difference being the emphasis on specification of a broader set of dynamic inter-sector linkages than in most DCGE models), private households and firms, the informal economy and trade. Market price dynamics are mediated by product stocks (e.g. inventories). The technology core includes factors that influence energy efficiency, pollution, agricultural productivity and linkages between education and labour productivity. The social core includes population dynamics (one-year age cohorts are specified for each sex), health care, food and nutrition, education, the dynamics of HIV/AIDS and linkages to both production and human development indicators. The resource core describes energy supply and demand, land use, forest dynamics, water supply and demand and their linkages to production, human health and environmental quality indicators. The environmental core consists of calculations for greenhouse gas emissions and total suspended particulates material (TSPM). The 'rest of the world' core includes migration, cross-border pollution, trade and financial flows and the impacts of various international agreements. The model also provides a core of indicators that link model outcomes to national goals, MDGs, UN Development Assistance Indicators and other performance benchmarks used by international agencies. Although this is a spatially aggregated model, it allows assessment of income distribution and poverty rates (although exactly how it does this is not documented). The model can be used to simulate trajectories over time for a 20–25 year time horizon. In the model documentation, Millennium Institute (2005) provided some model evaluation results but little discussion of policy scenarios. In part, this appears to arise from the fact that the model is intended more for broad use by policymakers than as a research tool. Key strengths of this approach are its extension of CGE model concepts to a broader range of dynamic linkages and policy issues, direct connection between model outcomes and indicator variables used by development agencies, and the ability to undertake 'causal tracing' that 'allows the user to see what causes a specific result for any variable'.

Agent-based models

According to Axtell (2000), an agent-based model consists of individual agents that have both 'states' (current characteristics or status) and rules of behaviour. These agents are assumed to

interact directly with one another and a 'social macrostructure' (that is macro outcomes) arise from these micro-level interactions. (This derivation of macro-level outcomes from individual sets of micro-level conditions and rules is one element of what is referred to as 'emergent properties' of systems in other disciplines.) Often the use of agent based models is motivated by 'a basic dissatisfaction with rational agents' and therefore 'essentially all the agent-based models that have appeared to date involve some sort of boundedly rational agent'. Axtell (2000) suggested four principal advantages of agent based models. First, as noted, the rationality of agents can be manipulated. Second, agent heterogeneity can be easily addressed, which avoids the need to aggregate across agents (e.g. to assume 'representative agents'). Third, because 'solving' the model involves allowing agents to interact over a certain time frame, 'there results an entire dynamical history of the process under study'. Thus, there is no need to focus only on equilibria (should they exist). Finally, it is typically straightforward to allow interactions among agents to be mediated by space or (social) networks or both, which is often an important characteristic of economic interactions. One disadvantage that is noted is that, although each run of an agent-based model establishes a 'sufficiency theorem' (i.e. 'given these initial states and rules, the outcome will be X'), a single run does not provide any information on the robustness of these sufficiency theorems (i.e. we do not know 'how much do the initial states or rules have to change before the outcome is no longer similar to X').

Axtell also identified three situations in which agent-based models can be useful. First, 'when numerical realizations are relevant, agents can perform a variant of classical simulation'. One example is when a 'social process under study' can be fully represented by mathematical relationships and solved analytically or numerically, ABM can still serve as a useful check on any numerical solution. In the case of stochastic models, it is also possible to conceive of each realization of a stochastic outcome as an agent. When analytical models are only 'partially soluble' (Axtell noted that 'it is seemingly on in *very* restrictive circumstances that one ever has a model that is completely soluble, in the sense that everything of importance about it can be obtained solely from analytical manipulations', with the emphasis his), because its equilibria are unknown, stability of the equilibria are undetermined, or the dependence of equilibrium[25] outcomes on parameters is not clear, then ABM can be a useful complement to analytical mathematics. In situations where analytical solutions do not exist (systems of nonlinear differential equations are an example), and the governing equations are highly nonlinear (so that they do not lend themselves usefully to numerical simulation), ABM are 'perhaps the only technique available for systematic analysis'. As a practical matter, Axtell noted the ongoing development of computing technology and ABM-related software, which will allow 'creating entire mini-economies in silicon… if we can just learn how to build sufficiently realistic agents…'. He noted also that there is a philosophical dimension to the emphasis on decentralized decision-making, in which outcomes emerge from individual agent decisions in ABM rather than the 'social planner with perfect information and infinite computing power' approach typically assumed in general equilibrium approaches.

Berger (2001) and Berger et al. (2006) described applications of ABM in agriculture, especially in 'less-favoured areas'. Berger (2001) noted that simulation models that predict the behaviour of individual agents often are based on optimization methods, with decision-

25. Axtell presumably emphasized equilibria here because he was writing for an audience of economists, for whom the concept of an equilibrium is of central importance. As noted, not all dynamic systems have stable equilibria.

making aggregated to the regional or sectoral level. (Note, however, that many optimization models are at the farm level, but he appeared to want to focus on models that predict more aggregated outcomes.) One reason for this type of simulation model, he asserted, is that they are less demanding of aggregate data than econometric models. Berger (2001) cited Hanf (1989) in noting that there are essentially two extreme prototypes of agricultural sector models: simultaneous equilibrium (which essentially assumes perfect market coordination and a common 'sectoral' utility function) or representative individual farms (which are then aggregated to compute a sector-level result).

The second approach 'seems to be a preferred model' if the sector under study is characterized by imperfect markets, behaviours other than profit maximization and adjustment delays (i.e. in most developing country situations). He noted that the simultaneous approach has weaknesses, including aggregation errors, a tendency to overspecialize in certain activities (often due to omission of relevant risk and consumption preferences from the objective function), lack of explicit interaction between actors (e.g. individual farm households; which he equates to absence of transactions or information costs) and insufficient attention to spatial factors. Berger (2001) specifically noted that 'the explanatory power of these modes is rather moderate for research questions that involve the diffusion of innovations or locally-adapted resource use'. He went on to argue that a combination of individual-level optimization models combined with a 'spatial cellular automata' will allow for appropriate specification of heterogeneous agents and their interactions (especially in local land and water markets) and thus better predictions of the dynamic time path of adoption of innovations and likely outcomes.

Berger et al. (2006) noted that:

> The scientific challenge is to apply bio-economic models when policy interventions and/or environmental changes are likely to cause large differences in individual policy responses…. Another challenge for bio-economic modelling is to allow for a sufficient degree of spatial and temporal complexity, since changes in the nature environment, the market environment, and the introduction of improved technologies typically involve long-term interacting processes. *This is especially important for the* ex ante *evaluation of plant breeding programs which will usually take about 10 years to release newly adopted varieties.*

The emphasis above is mine, because it highlights assessment of future technologies (including both crops and livestock) as a key motivation for modelling systems evolution. Berger et al. (2006) also noted that 'there are several policy questions in the context of agricultural development of LFAs, where MAS simulations may generate useful information for decision-making on public investments in R&D and targeting of policy interventions'. These include 'Should funds be spent on crop breeding for stress resistance or in research for improved crop management?' and 'Should micro-finance be promoted or should agricultural inputs be subsidized?' These are the types of questions that any SE modelling approach should be able to address over a relevant time horizon.

Berger model of Chilean regional agricultural dynamics

In a specific example of a 'multi-agent cellular automata' model, Berger (2001) sought to address four questions related to the diffusion of agricultural technologies and structural change in a region of Chile:[26]

- What are the likely patterns of diffusion for the innovation?
- Will the innovations create sufficient incomes but also reach traditional farmers?
- Will there be important structural changes that result from adoption (i.e. the treadmill effect)?
- Will there be changes in the use of water from water-saving technologies?

To assess these questions, he developed a modelling approach with heterogeneous individual optimizing farms that interact to share information and exchange land and water (use rights rather than ownership). He noted that this basic approach could be called 'a highly disaggregated farm programming approach with inter-household linkages'. (Thus, the distinction between multiple household (disaggregated) programming models and ABM is at times a bit blurred.) Adoption of innovations is 'conceptualized as a farm investment problem under uncertainty', in which farms face heterogeneous net benefits from adoption and all other costs that relate to the farmers' management capacity (termed 'adoption costs'). This is related to a set of assumed adoption thresholds based on a frequency-dependent diffusion model with five adoption categories. The optimization by each farm is characterized as 'sub-optimizing with feedback' in that the 'agents attempt to maximize their expected income in a sequential, local optimization procedure that takes into account the agents' previous experiences'. Income thresholds incorporated into the model allow for farm exits (and thus, changing farm structure).

The model itself is written in C++ and 'permits modular extensions to include, e.g. ecological constraints or… interfaces with geographic information system (GIS) applications'. The model was evaluated for farm-level and sector level predictions using statistical tests, robustness (extreme conditions) tests for average income and on-farm labour allocation and the results were considered 'plausible'. Policy experiments involved modification of a variety of model elements exogenous prices (to examine the impacts of trade agreements), credit market conditions, water supplies, price and water supply expectations and technology adoption costs (related to information availability). Results discussed include the percentage of adopters over time for *campesino* and commercial farms, spatial adoption of irrigation technologies, agricultural incomes, and the change in the number and sizes of farms. At the end of the day, he noted that 'fully integrated economic and ecological models for policy development and evaluation remain an ambitious undertaking', and 'the predictive capacity of such models will be mainly restricted by their inherent assumptions with regard to human decision-making rather than by ecological parameters'. The model results suggest that 'once the practical problems of combining different types of models are solved, GIS-based integrated multi-agent models will become a powerful tool for policy analysis and natural resource management'.

26. Note that these questions have a significant overlap with questions that should be of interest *vis-à-vis* adoption and impacts of innovations, along with SE.

Castella et al. community simulation model in Vietnam

Another application of 'multiple agent simulation' (MAS) in agriculture is provided by Castella et al. (2005), who assessed the evolution of diversity in the farming systems of northern Vietnam during a transition from cooperative land management to household level land management. A principal objective was to understand the mechanisms of land-use change, to integrate interdisciplinary knowledge relevant to understanding these processes and identify likely driving forces of change. The empirical model was based on a conceptual model of farming-system differentiation developed based on household survey data. The conceptual model was based on two key variables: the ratio of household labour to total household members ('mouths to feed' in the parlance of the article) and access to lowland fields suitable for paddy rice production.

The empirical model was a 'rule based' formulation (often, this terminology appears to be used to emphasize the contrast with optimizing behaviour or behaviour based on mathematical response functions, and in this case results is a rather large set of 'if–then' statements). The 'agents' in the model are households, who are assumed to make calculations of paddy rice production, rice surplus or deficit, food requirements for the family (based on fixed rice quantities per person, without regard to age), then decide how to distribute the remaining labour between upland rice and cash crops, calculates income needs and availability, a cash stock and (if sufficient cash is available) water buffalo purchases. The model is initialized with 50 households comprising 246 'virtual' individuals. The 'cells' in this model are a 50 × 50 grid of 1000 m^2 plots. Each cell is characterized by its distance from the village and its current use. Land use will change depending on the individual agents needs over time.

The effects of 'cooperative' vs. 'household' land management are simulated through changes in the distribution and restrictions on use of cells used for paddy rice production. The model is simulated for eight years (i.e. with a time step of one year), and the results are deemed (rather loosely) 'consistent with the actual changes in forest cover'. The authors reported aggregated land use for the grid, which shows declines in forest and tree cover. They then tested the extent to which the initialization conditions influence the outcomes by modifying demographic characteristics of households, which has an influence on the prevalence of cash crops and aggregate household incomes. Noting that one limitation of the model was its lack of interactions among households, the researchers developed a role-playing game based on the basic logic of the model. This game was then used to develop a set of rules governing farmer interactions and the model was subsequently modified. This approach represents an intriguing, participatory approach to model development and application, although they noted that the introduction of the additional interaction rules reduces the generality of the model and its simplicity.

Sulistyawati et al. community land use change model in Indonesia

Another agent-type model (although it is not explicitly called such by the authors) was developed by Sulistyawati et al. (2005) to explore spatially-explicit land use strategies in a community in Kalimantan, Indonesia. They noted that the approach is 'essentially a combination of individual-based modelling widely used in ecology… and 'microsimulation' modelling that has been used in the field[s] of demography, anthropology, sociology and economics'. Their model integrated

the demographic, socio-cultural, economic and ecological factors affecting land use decisions in 'swidden agricultural landscapes'. Households are represented as discrete entities, each having unique attributes such as number of members and property ownership. As in Castella et al. (2005), they adopted a 'rule-based' approach 'as opposed to mathematical or statistical approaches'. The dynamics of the system are simulated from a set of rules represented entirely as 'if–then' statements. The population model defines a closed community (i.e. population dynamics depend only on births and deaths) in which probabilities of death, giving birth and getting married depend on an individual's age, sex and marital status. The land use module reflects local preferences for subsistence food production (rice) from swidden over cash crop (rubber) production. The selection of swidden is modelled as an explicit spatial process where land use decisions are determined by distances to various locations (housing, river, other household's), vegetation, ownership and topography.

In a manner similar to Castella et al. (2005) the production evaluation module assumes that the household evaluates whether current food and cash needs can be met, and these influence the degree of effort allocated to rice vs. rubber. The vegetation dynamics module simulates discrete changes from one land use state to another. The dynamics of land used both for rice and for rubber follow predetermined aging-chain structures. The validation approach noted that the purpose of this model was 'not so much on the exact magnitude of data agreement but more on the range and plausibility of the trend in model output'. The rate of forest disappearance and the development of inequalities among households provide qualitative evidence for the basic model formulation and initialization parameters. Simulation experiments conducted with the model included scenarios with growing or constant populations, and with two alternative land use rules, one based on (traditional) preferences for subsistence production and the other based on minimizing the labour inputs required to purchase sufficient rice for household consumption (which could imply using labour to grow rubber that would then be sold and the income used to purchase rice). They reported how population and land use varies over a 75-year period in response to these factors, the percentage of households with high rice self-sufficiency and the average length of fallow. They noted, however, that 'many aspects of community life are assumed to be constant for 75 years' such as technology, zero-migration and household preferences, which are limitations of the existing approach.

Wallis et al. agent-based model of Hispanic acculturation

These authors reported on a modelling approach that integrates ABM with feedback mechanisms (SD models) at both the individual and aggregate levels. The objective of the modelling exercise is to assess the future 'social integration' of the Hispanic population in the US. There are two viewpoints, one which stresses the likely assimilation of Hispanics, similar to other previous 'immigrant' groups, and the other predicts that Hispanics will remain a distinct and separate subculture. At the level of the individual, a decision model concerning education, income, and fertility is incorporated into an aging chain. Current decisions about education and childbearing, for example, influence future income (which also influences future fertility) through feedback processes and delays. Individuals also decide whether to live in a 'primarily Hispanic community'. The individual decisions are driven by probabilities conditioned on current state (e.g. age, gender, education, income). At the macro level, aggregated individual choices (that lead, for example, to the aggregate 'Hispanicness' of a community) feed back to affect individual behaviour (e.g.

to the decision of individuals to live in that community). The authors noted that although the individual-aggregate behaviour linkage specified in the model will tend to lead to concentrations of the Hispanic population, other factors such as individual decisions to learn English and pursue distant educational opportunities can offset this tendency to a certain extent. Wallis et al. (2004) hypothesized that 'acculturation processes' as a system of feedback loops, with 'acculturation level' determined by the availability of 'first culture clusters' and degree of exposure to second cultures. The latter is determined in part by the desire and ability to gain economic or educational opportunities outside the first culture cluster.

An empirical application of the model is developed for the state of California. The model is simulated for 1950 to 2020, and county-level Hispanic population densities are shown for 1950, 1990, 2000 and 2013. They also reported 'acculturation index' values by age over time, demonstrating that there is a 'bifurcation' of the Hispanic population into first-generation Hispanics with a relatively low degree of acculturation (to mainstream US culture), limited English skills and low incomes, and a second group of later-generation Hispanics who have a much higher degree of acculturation, stronger English skills and higher incomes. They noted that additional extensions of the model could be made to better model 'cultural values' (through the introduction of various 'soft variables'), but that variables of interest to marketing firms (like purchase behaviour) could also be simulated.

Other simulation modelling approaches

In many of the examples above, the modelling efforts were based on either conceptual frameworks or modelling methods that has been formally defined in the literature. In some studies, of course, there is either no specific appeal to a formally-defined CF or methods from the literature (other than the generic term 'simulation model'), or the research applies a variety of such methods in a rather *ad hoc* manner. It should be noted that there is nothing inherently superior in the use of formally-defined frameworks or methods to develop dynamic simulation models.

The use of 'integrated models' that combine multiple modelling approaches in one model structure or separate models that are designed to interact with one another (e.g. outputs from one model provide inputs for another model) has become more common. Lambin et al. (2000) stated that 'these… models are referred to as integrated models, although in many cases they are better described as hybrid models because the degree of integration is not always high'. They noted also that in the land-use change literature Wassenaar et al. (1999) demonstrated how a dynamic, process-based crop model could be applied at the regional scale through the derivation of statistical relationships between the modelled crop productivity outputs and easily-mapped soil parameters. White et al. (1997) also demonstrated the use of a land-use change model that combined a stochastic, cellular autonoma approach with dynamic systems models of regional economics. Although these modelling efforts have provided useful insights about complex land-use systems, the effort required appears to be substantial. Lambin et al. (2000) remarked that the trend toward integrated models implies both increasing size and complexity, and that 'one needs to be aware that such models are no longer within the domain of individual researchers, but are increasingly developed within the framework of large, multidisciplinary research teams'. Despite this, Lambin et al. (2000) considered dynamic simulation models as a useful approach, arguing

that 'dynamic simulation models are better suited to predict changes [in land-use intensity] than empirical, stochastic or static optimization models, although some stochastic and optimization models may be useful in describing the decision-making processes that drive land management. Moreover, it appears that an integrated approach to modelling (that is multidisciplinary and possibly cross-sectoral) will probably best serve the objective of improving understanding of land-use change processes including intensification'. Many of these same assertions are likely to apply to systems evolution dynamics more generally.

The examples below illustrate a number of alternative methods (e.g. population matrix) and 'integrated assessment' approaches that are relevant for consideration of systems evolution modelling. Three of the examples, Texiera and Paruelo (2006), La Rovere et al. (2005) and Bouwman et al. (2005), directly addressed dynamics in livestock systems. Letcher et al. (2006a, 2006b) and Vatn et al. (2006) provided examples of integrated modelling frameworks.

Texeira and Paruelo analysis of sheep flock dynamics in Patagonia

The objectives of this study were to explain the importance of regional factors (i.e. climate, desertification) in explaining trends and fluctuations in sheep numbers in Patagonia, and to examine the contribution of 'demographic processes' to the observed population declines. Using data from four flocks in the region, they estimated 'synchrony' based on the average cross-correlation coefficients between ranches of log-transformed first differenced series of animal numbers and growth rates. Significant synchrony in flock dynamics would reflect the action of regional factors, because if different ranches have similar patterns of these variables, then it must be 'regional factors' that caused them. These factors are those other than 'above-ground net primary production', which they defined as the principal 'ecological covariate' of population growth rates.

Texeira and Paruelo (2006) used 'matrix population models' in which the vector containing the number of individuals in a [life] stage at a time t is multiplied by a square matrix consisting of stage specific 'demographic rates'. Post-multiplying the matrix by the vector yields a 'trajectory' of each stage over time. They noted that 'Matrix population models are widely used as tools to derive management practices of endangered wild populations and exploited populations'. They employed both deterministic models (in which the 'projection matrix' elements are constant over time) and stochastic models (in which the elements of the matrix are selected at each time t 'according to a probabilistic rule'. The latter approach allows (a really rather non-specific) inclusion of 'environmental variability in demographic rates'. They used Monte Carlo simulation approach with 10 thousand replicates to calculate confidence intervals for the effects of environmental variability on population dynamics.

Ultimately, after a good deal of mathematics, what they provided as results for the herd dynamics are an exponential decay pattern for the deterministic model (which derives from the model essentially being a linear (difference) model with a negative coefficient for the growth rate) and similar patterns with confidence intervals for the two stochastic model formulations presented. The conclusions arrived at 'the population dynamics of sheep flocks seem to have a strong biological constraint' and 'a more mechanistic approach is required to identify the controls of the demographic rates that generated the observed dynamics' suggests that these results do not lend

themselves to assessment of policy options or impacts of specific environmental effects (e.g. El Niño). Perhaps other 'matrix population models' are more developed to allow this sort of analysis, but the systems ecology literature seems to have moved beyond using linear matrix models to assess multiple species population models (Kitching 1983). Although the specific implementation of this studies leaves certain elements to be desired, it is possible that this approach may be useful for further understanding of systems evolution when natural populations (of plants or animals) are involved.

La Rovere et al. model of farming systems evolution in Niger

The key questions raised in this paper concern the evolution of farming systems in southwestern Niger under privatization of pooled common resources (especially grazing) and the impact of intensification (alternative combinations of inputs like manure, labour, fertilizer and animal traction) on livelihoods and 'agro-ecosystem health' (La Rovere et al. 2005). To address these questions, this research integrates elements from 'hard' (biophysical), 'soft' (social and institutions) and 'complex' systems thinking (co-evolution of systems and their social, institutional and policy contexts as described in Norgaard 1984). The basic approach is to link a farm-household model using LP maximizing an inter-temporal utility function with an '*ad hoc* routines' to aggregate land, labour and forage resources to the community level and to allow 'spatially explicit scenario outputs suitable for GIS visualization'.

One emphasis is on the nutrient dynamics of the system, with 'an algorithm' developed to account for farm-specific nutrient imports and exports via livestock. A technical coefficient generator (TCG) was developed to quantify 'agricultural activities and agro-ecological processes'. In the empirical implementation the 'aggregation linkages' are somewhat limited (this is essentially a farm-level analysis, but with assumption made about how access to common resources will change with 'privatization'). However, this study combined a farm-level optimization approach with an aggregation approach. With additional aggregation linkages (as in Berger 2001 or Deybe 2001), this approach could probably be applied to other production systems.

Bouwman et al. model of global grassland and livestock distribution in 2030

This research used an 'integrated' model (IMAGE; initially developed 'to explore the long-term dynamics of global environmental change) to assess potential changes in the spatial distribution of animals and grasslands from 1995 to 2030. Although the IMAGE model is described as including 'ecosystem, crop and land-use models… to compute land use on the basis of regional consumption, production and trading of food, fodder, grass and timber, and local climatic and terrain properties', little information is provided about these elements in this paper. The country-level projections of livestock production in 2030 from Bruinsma (2003) were disaggregated into four production systems (mixed and landless milk and meat, pastoral milk and meat) using various feed conversion factors, projected animal numbers, dietary composition and 'grazing intensity' to arrive at total estimates of areas required for mixed and landless grassland and pastoral grassland areas.

Some of the assumptions seem questionable at best. For example, to disaggregate the total livestock production into the mixed and landless and pastoral systems, they assumed that the fraction of the

animal population in the pastoral system will *decrease* at half the percentage rate of GDP *increases*. The feed composition was assumed to be the same in 1995 and 2030, but feed conversion improved during this time frame. For the years after 1970, land cover is calculated by the IMAGE model, in which 'expansion and abandonment of agricultural land is based on a number of rules based on the land's suitability, distance to existing agricultural areas, urban areas, rivers and a random factor'. Grassland areas were further subdivided into mixed and landless systems under the assumption that 'mixed and landless systems were assumed to occur in mosaics with arable land, while grid cells with pastoral systems have less arable land'.

The key outputs are maps of projected animal densities, areas of grassland used for different regions, and production per hectare. This approach seems to use primarily exogenous (assumed) drivers of change, filtering them through a relatively limited number of (non-process based) conversion factors in order to allow spatially-oriented predictions. The land-use modelling component appears to be largely based on past relationships, and limited numbers of feedback relationship are included. This is acknowledged by the authors when they stated that 'in many countries, the degradation of grasslands may lead to decreasing productivity. Where such problems occur, the projection for 2030 may not be realistic…'. Moreover, there is little recognition that for mixed and landless production systems (and much less frequently pastoral systems) there need not be a direct correspondence between the location of livestock production and the location of feed production, and that this spatial disaggregation will likely become more frequent and important. In addition, there appears to be limited or no ability to conduct sensitivity or policy analyses with the model.

Letcher et al. integrated assessment model

Letcher et al. (2006a) described an 'integrated modelling toolbox' that has been developed to assess dynamics of water use at the 'catchment' scale. They noted that 'trade-offs between economic, social and environmental outcomes must be considered to improve the sustainability of catchment systems', and that 'these types of complex interactions lend themselves to analysis by modelling approaches'. They based their modelling work on the 'Integrated Assessment paradigm' (discussed as one conceptual framework above). They defined a 'nodal-network approach' that combined household-level decision models with a nodal network to represent aggregated points of water extraction. Households are categorized into a number of 'resource management units' and household decisions are aggregated by 'summing up decisions of each RMU type present at the node'.

The 'toolbox' consists of a number of models, including a household decision model, a decision disaggregation model, a biophysical modelling 'toolbox' (with a crop model, a hydrological model, a water allocation model and a soil erosion model) and a socio-economic impact simulation model. An empirical implementation of the model is developed for water catchments in Thailand. Land-use decisions based on wet and dry-season LP formulations that maximize expected net income (during the current period only; only for annual crops) subject to and water availability are disaggregated to the RMU level, and these decisions are evaluated using the biophysical models. Exogenous climate data are used to influence water flows, erosion, crop yields and irrigation demands. Yields, water use, water availability and soil erosion from the biophysical models are provided to the socio-economic impact model to determine impacts on outcomes of interest (cash per household, total household income from agriculture, off-farm household income).

The models run are on different time steps. Letcher et al. (2006b) described in greater detail the process of sensitivity analysis and model testing, using a 'scenario-based approach'. This approach 'allows scenarios to be generated as inputs to the toolbox and a range of biophysical and socio-economic indicators to be produced as outputs'. They noted that this is preferred to an 'optimization' approach in which 'a subjective best outcome' (for the system as a whole rather than at the farm level) would need to be specified. They also suggested that model purposes other than prediction or forecasting are most appropriate for IA-based models, such as 'to understand the relative magnitude and direction of changes of system outcomes… in response to changes in policy and other drivers'. Although they did not present them, the models can generate trajectories for the behaviour of variables of interest. In terms of the integrated modelling process they recommended, they noted that 'focus should be on developing a conceptual framework for integration of system components and populating this with relatively simple models before emphasis is placed on developing and incorporating more complex representations of component processes'.

Vatn et al. regional model of agricultural pollution in Norway

This study presented a method for analysing the effect of policies to reduce pollution from agriculture. It combined elements of systems analysis, multiple scales and optimization of farm decision-making. They begun by noting that 'in a complex system like the agronomic, there is [a] great chance that 'single factor' manipulations… result in cumulative negative impacts across processes and over time'. Thus, 'solutions… are best found by looking at the whole system, including both the natural systems involved and the economic agents operating them'. Thus, they adopted a systems perspective as the basis for models' development and interaction. The problem to be addressed is 'the most serious pollution problems related to agriculture, namely, the losses of various nitrogen compounds, soil and phosphorus, and pesticides to the external environment'. They developed a 'modelling system' consisting of eight process-based models and a 'specially designed aggregation routine'. The goal is to integrate across scales (temporal and spatial) disciplines, and processes (to address feedback effects). These models are used to estimate effects dealing with hydrology, temperature, plant dry matter yield, N absorption, N turnover and leaching, weed development and pest management, ammonia losses to the air and into soil, P and particulate N and farmers' choices of field-specific practices. They used a series of coordinated 'pre-runs' to estimate appropriate expected values for crop yields and mineralized N. The principal inter-temporal linkages appear to be through soil nutrient accounting, done on a yearly, iterative basis.

Farm choice models are based on mixed-integer and nonlinear programming methods, and assume that farmers maximize expected profits (presumably in each period). The statement is made that 'to maintain consistent solutions, a module called Integration is run as a first step in each scenario setting the constraints necessary to avoid inconsistent combinations of practices'. (It is not entirely clear what this means.) To aggregate the results to a larger spatial scale, they defined a set of farm types and farm type fields along with a proportion that each represents in the total. They applied the model empirically to four regions in Norway using weather data for 1976–97 and a 1995 base year. They run the model for a simulation period of 22 years, which is 'considered sufficient to cover weather variations across years'. The main 'validation' approach is to compare point predictions or period averages for observed and simulated crop choices, fertilizer use, crop yields in the region (no statistical tests or other evaluation approaches are discussed; no trajectories are

provided although presumably they could be). They concluded that 'results are mostly in line with what is observed'. Essentially, this can be viewed as a set of farm-level models that are aggregated to the regional level via proportions of each farm type. There is little discussion in this paper concerning the 'economic incentives' (e.g. prices) other than to note that 'by changing these, we change the incentive structures for model farmers'. Thus, they did not make clear what (presumably exogenous) assumptions are made concerning prices over the 22-year simulation period.

Comparative assessment of systems evolution modelling methods

This section discusses the overall characteristics of various modelling approaches to assess systems evolution, and summarizes a set of implications (recommendations) for future systems evolution modelling. The characteristics of importance for this comparative assessment include the strengths and limitations of methods (either in principle or as usually applied), their data requirements, the effort required for model development (due in part to the availability of commercial software), their ability to be used in a participatory manner, how readily interdisciplinary content (e.g. involve researchers from multiple disciplines) can be incorporated, and the degree to which they can be integrated with other methods.

Comparative assessment of methods

The characteristics of the descriptive approach and the seven quantitative approaches differ in important ways (Table 6). These characteristics imply that different approaches will be most appropriate under certain conditions. For example, descriptive analyses will be most beneficial in situations where little previous formal modelling work exists, time-series data on key relationships are available or can be relatively easily collected and there is a need for exploratory analysis about underlying statistical and causal relationships. Descriptive methods often will be useful not for direct inferences about future outcomes, but as a basis for further conceptual and simulation model building. Statistical modelling will be most useful in situations where there are adequate time-series data available to test hypotheses about empirical relationships among a set of variables (those relationships presumed to hold in the same manner in the future) and as a basis for parameter estimation for other types of models.[1] The use of time-series analysis may be helpful when longer time series data are available for a limited number of variables of interest, and the emphasis is on prediction alone rather than structural understanding. Variants of time-series methods that include structural variables may be most useful when the periodicity of structural data is significantly larger than that of some phenomenon of interest (e.g. monthly vs. annual data).

Dynamic optimization methods can be useful for understanding systems evolution when a clearly-stated objective for the system can be specified (usually by policymakers). In this situation, optimization models often can identify values of the policy parameters necessary to achieve the objective, resultant outcomes for particular target groups, and marginal resource values. Dynamic CGE models will be most appropriate when the questions of interest are likely to involve general equilibrium effects, such as when agriculture is a significant share of GDP, the scale of the model is national, or when analysis is desired of broader trade or agricultural policy effects.

DCGE modelling focuses primarily on economic relationships and is facilitated, of course, when a previously-developed social accounting matrix is available that can be modified for the specific purpose of the study. System dynamics models can be applicable in a wide variety of contexts where the focus is on systems evolution.

1. Sterman (2000) noted that it will often be appropriate to use alternative statistical methods such as Kalman filtering within the context of an appropriately specified dynamic systems model rather than more typically used econometric methods. He also stressed that in practice, it is important to use judgment and statistical methods together to estimate simulation model parameters.

Table 6. *Comparative summary of selected methods for analysing systems evolution*

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Descriptive	Detailed written description of past events and interpretive analysis, then (qualitative) inferences about future	Can provide a strong conceptual and empirical basis for understanding past events; helpful for other model development; comparative case studies	Qualitative predictions; possible inconsistency among predicted variables; may not predict structural changes; no sensitivity analysis; selective inferences	Varies, but can be quite extensive and time-consuming; primary and secondary time series and cross-sectional data collection efforts are common	Conceptual model development may be extensive or not; no quantitative model development, general software use (e.g. for presentation, simple statistical analyses)	Not typical, but perhaps has potential	Diverse content can be integrated, but issue is consistency among variables	Can serve as a useful basis for other modelling efforts
Statistical	Establishment of statistical relationships among key variables through regression or correlation analysis (many variants of these approaches); may or may not be theory-based	Commonly used, hence familiar; allow statistical hypothesis testing and delineate confidence intervals; can test for previously unknown relationships	May not predict the future well if 'latent dynamics' ignored; causality may not be assessed; neglect of 'soft' or other variables for which no data exist; limits on functional forms; poor prediction record (according to some authors); sensitivity and policy analysis can be limited	Varies, but can be extensive; primary and secondary time series and cross-sectional data efforts are common; 'missing' data may require proxy variables	Many software are available that facilitate model development; often software is used to determine relevant variables rather than their selection a priori by the researcher	Not typical, and probably little potential	Can integrate content but typically in limited ways due to the nature of the data and (often assumed) linear relationships	Can use information from descriptive studies; can estimate coefficients for use in other types of modelling; related methods can be used in simulation model evaluation (e.g. goodness of fit)

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Time series	Statistical models that predict future outcomes based primarily on past values of a data series, rather than on ‘structural’ relationships among variables; linear ARIMA and VAR models common in applications	Allows statistical hypothesis testing and delineate confidence intervals; can test for previously unknown relationships; fewer data requirements than structural models	Limitations of statistical models apply; determination of appropriate formulation from data can be a challenge; assumed linear models can predict only certain dynamic behaviours, so TS models may misrepresent some dynamics	Varies, but can be extensive, especially the number of observations required for a given variable	Software is available but less common than for other statistical methods; determination of formulation requires judgment and can be time consuming	Not typical, and probably little potential	Probably more limited ability to integrate content than for other statistical methods	Not typically integrated with other methods

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Dynamic optimization	Specification of an objective function for the system of interest, a set of decision variables and a set of relevant constraints; the objective function is then maximized or minimized subject to the constraints (many variants exist; most recent are evolutionary algorithms)	Given an objective function, model determines optimal decisions; can incorporate both economic and biological information; can address multiple objectives; allows sensitivity and policy analyses and determines marginal values of resources	Optimization assumption may not describe actual behaviour (particularly for systems, may be useful as benchmark); characteristics of agricultural problems (e.g. nonlinearity) can make computation difficult or sub-optimal; may require substantial computational time; dynamic models often assume equilibrium in each time period; aggregation issues can be important	Models often rely more on secondary data, with parameters estimated previously or assumed and tested, so can be developed in absence of time series data	Many software are available, ranging from simple to complex; nonlinear dynamic models typically will require more programming and evaluation time	Not typical, and probably little potential	Good ability to integrate content if this can be structured as a part of the objective function, activities or constraints. Typically, this is done through discrete activities rather than continuous relationships; interaction effects may be problematic	Can use information from descriptive and statistical studies; can be integrated with other simulation approaches, system dynamics, and agent-based models

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Dynamic CGE	Models based on a macro-economic equilibrium framework including all markets (essentially, optimization by all relevant agents), with dynamic linkages that typically involve growth in capital or labour	Captures a broader range of economic feedback effects (e.g. linkages between agricultural production and national income), which may be important even at local scales; can incorporate both economic and biological information; can address multiple objectives; allows sensitivity and policy analyses	Equilibrium (optimization) assumptions may not be appropriate; usually employ high degree of aggregation of inputs and products; form of production functions for products generally limited to a few choices; incorporation of biological or environmental information often simplistic and(or) ad hoc; the nature and extent of dynamic linkages is often limited; GE effects not always empirically important	Varies, but a Social Accounting Matrix delineating input–output relationships must be developed as relevant for the system; often rely on secondary data for parameters estimated previously, so can be developed in absence of time series data; a network of CGE modellers may provide a starting point for data needs	Various software exist (e.g. GTAP framework, GAMS) but these generally require programming experience on the part of the researcher; model development and testing can require significant time and resources	Not typical, and probably little potential	Ability to integrate primarily through types of effects in production functions and or through dynamic linkages; both are often simplified to be consistent with other elements of the model structure	Often, a form of optimization model; not typically integrated with other methods

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Dynamic Partial Equilibrium Models	Models of a specific market or interacting commodity markets, but without aggregate income linkages	Can capture effects of interventions appropriately when aggregate income linkages unimportant; typically allow more policy and technology detail	May not adequately reflect aggregate responses for sectors that comprise a significant proportion of national economic activity; can be theoretically inconsistent	Varies, but generally less than required for DCGE models unless a great deal of production or policy information is included	Various software support model development, but requires programming experience; model requires significant time and resources	Not typical, and probably little potential	Ability to integrate primarily through types of effects in production functions and or through dynamic linkages; both are often simplified to be consistent with other elements of the model structure	Often, a form of optimization model, not typically integrated with other methods
Differential Equations (System Dynamics)	Systems of (nonlinear) differential equations solved by numerical integration; focus on systems approach, endogeneity (model boundary definition), stock-flow feedback structures, causal relationships, disequilibria, broad variable definitions	Can represent a broad range of potential dynamic behaviours; stock-flow structure enhances physical consistency; addresses disequilibria and 'bounded rationality' decision processes; facilitates interdisciplinary models and group learning	Generally provides better treatment of intertemporal dynamics than spatial dynamics; large models can become difficult to diagnose (small models can be 'too stylized')	Varies, but the SD approach often relies on information from numerical, written and 'mental' data (i.e. broader information sources); models often used with sensitivity analyses to assess data priorities; time series data for key variables helpful but not essential	Various software exist that allow flexible model building and testing; optimization routines and 'flight simulator' development quite common	Good potential, with well-developed group process methods established; 'flight simulators' can be developed for work with policymakers and other stakeholders	High degree of integration possible and demonstrated	Can use information from descriptive and statistical studies; can be integrated with optimization approaches and agent-based models, models similar to dynamic CGE models can also be developed

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Agent-based models	Models based on a number of 'individual' agents, each with states (characteristics) and rules of behaviour; often agents not assumed to be 'rational'	Ability to address alternative behaviours and multiple types of agent heterogeneity, dynamic time path (evolution) explicitly generated; does not assume equilibria; interactions among agents (through spatial or social networks) is possible; can demonstrate 'emergence' properties based on localized decision-making	Description of agents can be difficult or ad hoc; robustness of results not indicated by individual model runs; computational challenges	Varies, but often restricted to the characteristics of (heterogeneous) individual agents as a distribution of possible values; does not require time series data, but these helpful for assessing model outcomes	Some software exist, but many recent models coded in programming languages; model size can influence computational time required	Not typical, but perhaps has potential	Examples illustrate good possibilities for integration across disciplines	Can use information from descriptive and statistical studies; can be integrated with optimization approaches and system dynamics models

Method	General characteristics	Strengths	Limitations	Data requirements	Model development effort and software availability	Participatory/ group potential	Integration of interdisciplinary content	Integration with other methods
Other simulation approaches	Characteristics of approaches vary; some involve integration of multiple models and(or) approaches	Flexible with regard to modelling approach; often can generate dynamic time path information	Relationships within or between models can be arbitrary; often limited emphasis on economic factors; less appropriate for prediction	Varies, but can be substantial for integrated models	Varies, but more likely to be code developed specifically for project; integration of multiple models can require substantial effort	Varies, but not typical	Examples illustrate good possibilities for integration across disciplines	Varies, but multiple approaches can be integrated, particularly for multiple models

They will probably be most useful for development of what might be termed 'qualitative quantitative' models in which the objective is to develop relatively aggregated models to enhance initial understanding of the past and potential future behaviour, particularly when data are lacking or a participatory consensus-building process is of interest. The availability of easy-to-use SD software with good model evaluation tools and well-developed methods for participatory modelling are also strengths of this approach. Agent-based models also appear to have broad applicability, particularly in situations where heterogeneity of decision-making agents, non-optimizing behaviour and agent–agent interactions are likely to be important. Other simulation approaches, especially integration of multiple simulation models, will be most appropriate when a reasonably high degree of understanding about the various subsystems exists, when the production system of interest has multiple interrelated components, and when sufficient resources are available to support the multi-disciplinary team usually required for these efforts.

When are these various methods least applicable to analysis of systems evolution? Inferences about future behaviours should be made with a good deal of caution for descriptive analyses, statistical analyses and time-series analyses. This is the case because these methods are generally the least able to predict structural changes, tend to be based on a numerical database (rather than broader information sources such as written or mental information), have either limited restrictions on the relationships between variables (for descriptive analyses) or relatively restrictive relationship due to their functional form (e.g. linear regression or time-series models). It is often more difficult to undertake relevant sensitivity analyses with descriptive or statistical models given their structure and the assumed exogeneity of independent variables.

Dynamic optimization should be employed with care given that relatively few social and economic systems can reasonably be assumed to optimize the values of particular outcomes. Rather, optimization approaches in a systems context are most useful as normative benchmarks, as noted above. This admonition applies also to models that assume optimizing behaviour on the part of heterogeneous agents, as in Berger (2001). Dynamic CGE models are most appropriate for addressing a relatively narrow range of non-economic issues at one time (e.g. soil degradation or labour migration as in Glomsød 2001). Their lesser flexibility in incorporating interdisciplinary concepts and the need for an adaptable social accounting matrix (for the relevant production system, rather than a nation, region, or village) will likely limit their usefulness in production systems evolution work in the near future. Dynamic partial equilibrium models, often formulated as optimization models, can provide additional detail on production technology and policy options when aggregate income effects are presumed to be less important, and require less detailed information about each sector of the national (regional) economy. Many of the partial equilibrium models to date, however, with the exception of Deybe et al. (2001) have focused on national or multi-national regions rather than on the somewhat smaller scale presumed to be the focal point for future modelling of systems evolution.

System dynamics models can be applied in a broad range of settings and for a variety of behavioural assumptions. The modelling approach has been much more typically applied to highly aggregated models with a limited degree of spatial and individual agent heterogeneity. These could be significant limitations for the application of SD in production systems evolution modelling, but progress has already been made at integrating SD with other approaches (such

as agent-based models) and spatial-flow network models have also been developed (Ford 1999). One challenge with the more detailed SD models is that model calibration and evaluation can be more challenging as the models become more intricate. A key challenge for agent-based models is appropriate specification of agent behaviours and interactions, although often this can be addressed with sensitivity analysis to determine the importance of alternative behavioural assumptions to the outcomes. In addition, the development of agent-based software is less advanced than for optimization, DCGE and SD modelling, so this may impose a larger burden in terms of coding original programming (and de-bugging), especially when the agent behaviour is complicated (as in the optimizing agents of Berger 2001). Other modelling approaches will have varying caveats for their use. The use of integrated models poses challenges similar to those of the more complex SD models in that their calibration, evaluation and use can be more difficult. The required financial and human resources for integrated models should be available prior to their development, particularly because these models can have a relatively narrow (specific) range of appropriate use (e.g. global climate models).

Implications for analyses of systems evolution

What are the ultimate implications of this lengthy review? These can be summarized in terms of the appropriate modelling approaches in given circumstances, implications for systems evolution modelling in general and appropriate follow-on research activities to address systems evolution, technological change and policy options. With regard to the first of these elements, the implications are as follows:

No one method is universally applicable or superior. As noted above, each of the methods have advantages and disadvantages, and the applicability of the methods will depend in part on the nature of the problem, outcomes of interest, the information and level of understanding already available, and the financial and human resources available. Often, multiple modelling approaches will be relevant to assess the evolution of a single production system. Descriptive and statistical analyses will usually be most relevant at an early stage of understanding. Simple, more conceptual mathematical models can guide further model development and data collection, and more detailed integrated models can perhaps be developed to guide policy analysis and conduct detailed assessment of alternative scenarios. 'Triangulation' through the comparison of results from alternative modelling approaches, when resources permit, is likely to be a valuable exercise.

Systems approaches are preferred if the system is likely to display 'complex' behaviour. Although no one method is superior in all situations, it has been argued above that when the production system of interest may display dynamically complex (e.g. nonlinear) behaviour over time,[2] the use of a systems approach that emphasizes the development of both conceptual and empirical causal models will be most appropriate. This is because such complex systems can demonstrate 'surprising' changes in behavioural modes as a result of the interaction of factors endogenous to the system (even in the absence of significant external shocks). Even if only conceptual systems models are developed, these can be useful in the implementation of descriptive or statistical studies. In addition, more flexible and systems-oriented frameworks are likely to be necessary to address the

2. And as noted above, some authors like Sterman (2000) and Costanza (1993) argued that most coupled human-natural systems have this characteristic.

broad range of specific indicators that will be of interest for technology and policy development in diverse production systems. Thus, flexibility of the modelling approaches will be an important characteristic for their appropriate application.

Exercise caution in inferences from descriptive, statistical or optimization studies. Each of these studies can be useful, but inferences based on each of these approaches independent of others should be made with care. As noted above, these first two methods tend to have greater difficulty predicting structural changes, often are based on more limited (numerical) information and may imply relationships among variables that are either too restrictive or not restrictive enough. In addition, the conceptual models upon which these are based can sometimes be too narrow. The lesser ability to undertake model evaluation and sensitivity analyses with descriptive or statistical models can also limit the degree of confidence that the model is appropriate for its stated purpose. For optimization models, the key issue is interpretation of model results. As a mechanism underlying prediction of the future, optimization—for a system in particular—is probably not a good assumption. As a benchmark to compare with other possible features, optimization in a production systems context can be a useful tool.

Implications for systems evolution modelling in general include:

Scenario analysis is an important element of systems evolution modelling. Models to predict systems evolution will be most useful if they facilitate the development of alternative scenarios and their likelihood. As illustrated by the trajectories of change research (ILRI 2005), these scenarios or 'storylines' can be a powerful mechanism to address the (usually large) uncertainties of production systems evolution over a five- to ten-year period. The ability to conduct scenario analysis is connected with both sensitivity analysis and model boundary specification. The ability to conduct multiple simulations with reasonable turn-around time is an essential part of sensitivity analysis and model evaluation. The question of how to develop consistent 'storylines', as noted in Bruinsma (2003) is partly a matter of structuring a model to appropriately represent external (exogenous) effects, but it is also a matter of appropriately specifying the model boundary (i.e. what is endogenous and what is exogenous). An example of the latter is the ability to derive consistent scenarios of population growth and GDP growth. Partial equilibrium models will find this more of a challenge than CGE models for which GDP growth is endogenized (typically given exogenous population growth—although presumably this too could be endogenized).

Systems evolution models will be more useful if they allow assessment of technology and policy options. A stated purpose of the focus on systems evolution in this document is to better understand the types of technologies and policies that will be beneficial to particular stakeholder groups. The ability to conduct *ex ante* impact assessment in the systems evolution context will be a powerful complement to approaches that make a range of predictions about the future based only on exogenous variables. Thus, it is highly relevant, desirable and possible to include more detailed representations of technological and policy options in models of system evolution. With regard to livestock, a principal element of future dynamics will be growth in demand. Nicholson et al. (2004b) have shown that both incorporation of generic policy and technology options into a systems evolution model is feasible, and that the rate of demand growth can have important implications for the results of policy and technology interventions.

Greater emphasis should be given to undertaking and reporting model evaluation outcomes. The purpose of model evaluation, broadly speaking, is to find and correct errors, and to 'build confidence' that the model is appropriate for its stated, specific purpose. Expanding the scope of model evaluation efforts to include a variety of tests (as in Sterman 2000) in addition to statistical correlation measures will likely enhance the quality of systems evolution modelling research. This is in part because the numerical indicators of prediction are less appropriately applied in complex dynamic systems for reasons stated above. Of particular importance are efforts to understand how behaviour over time changes in response to changes in model boundary and omission/inclusion of various effects. In the current literature, these are often present as implicit maintained hypotheses.

A broader range of predictive indicators should be employed. As noted previously, the term 'prediction' is often more appropriately defined as 'point prediction' (a specific value at a specific time). This has caused a number of authors to state that certain methods (i.e. SD or integrated models) are less appropriate for 'prediction'. However, there are at least three kinds of prediction, and 'numerical' (point) prediction often can be usefully complemented by assessment of predictions of general behavioural tendencies (e.g. growth, decay, oscillations) and qualitative and quantitative differences that arise due to policy or technology interventions. There is an obvious linkage with the type of prediction employed and model evaluation, with point prediction being the most commonly used.

Greater attention should be given to modelling the impacts of technologies and policy interventions on specific groups, particularly the poor. For many analyses of systems evolution, it will be appropriate to attempt analyses that disaggregate the behaviours of, and outcomes for, groups of economic agents delineated by income or wealth status. This type of analysis is necessary if the effects on the incidence of poverty are to be understood. The Annabi et al. (2005) DCGE analysis of poverty dynamics in Senegal illustrates how this can be done, but also demonstrates the need for appropriately disaggregated data to allow reliable inferences from model simulations.

Areas of future research on systems evolution can benefit from the following:

Developing a set of integrated case studies of different production systems will greatly expand our knowledge. Although the issues of land use change, climate change and land degradation are notable exceptions, there are relatively few examples in the current literature that have a specific emphasis on prediction of future evolution of production or livelihood systems in agriculture generally or those with livestock more specifically. Thus, developing a series of case studies will be a useful contribution to understanding the future evolution of systems with livestock, enhancing methods to evaluate systems evolution and raising awareness of the importance of this type of work. These studies can most usefully highlight a number of different production systems in which livestock are important, adopt the approach of 'triangulating' with various modelling methods, and illustrate the conditions under which the various approaches are likely to be most appropriate. These efforts should undertake the other elements described above, including more detailed representation and evaluation of policy options, use of scenario analyses, and expanded model evaluation processes.

Systems evolution modelling can benefit from greater participation (and learning) by stakeholders. Most simulation models used for any purpose (not just prediction) are developed in isolation from the stakeholder groups. This approach, although most convenient for model developers, has three principal limitations (Vennix 1996; Sterman 2000). First, it usually results in less information (especially written and mental knowledge available only to stakeholders) being available for model development. Second, it often limits the acceptance of model-generated conclusions, because stakeholders often will view the model as an incomprehensible 'black box' and be reluctant to accept the information the model provides—particularly if the conclusions conflict with the outcomes of their own 'mental models'. Finally, some authors view model-building primarily as a method to enhance learning, not to make definitive predictions (e.g. Sterman 2000). Under this philosophy, it is essential to involve those decision-makers in the modelling process so that their 'mental models' are refined and expanded—presumably allowing more appropriate decisions to be reached. The development in the last decade of group model building approaches (Vennix 1996; and similar methods such as 'Focused Strategic Conversations' Paul Newton, Complex Systems Analysis Group, Boeing Corporation, personal communication), simulation games played with participants and 'flight simulators' that allow various types of decision-makers to assess the outcomes of interventions can be powerful tools for linking systems evolution models to effective actions.[3] It also provides a mechanism to facilitate linkages between the often-qualitative participatory research and action approaches, and the nearly-always quantitative approaches of simulation modellers.

In sum, there is a great deal of potential in the various methods described in this document to contribute to an enhanced understanding of the evolution of production and livelihood systems. To fulfil this potential, there is a need for additional systematic research effort and greater attention to the conditions under which the diverse modelling approaches can be usefully employed

3. Although the literature does not indicate this, these approaches could presumably also facilitate consensus about research priorities when used for dynamic *ex ante* impact assessment.

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