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Advances in farming systems analysis and intervention

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Abstract

In this paper, we recognize two key components of farming systems, namely the biophysical 'Production System' of crops, pastures, animals, soil and climate, together with certain physical inputs and outputs, and the 'Management System', made up of people, values, goals, knowledge, resources, monitoring opportunities, and decision making. Utilising upon these constructs, we review six types of farming systems analysis and intervention that have evolved over the last 40 years, namely: (1) economic decision analysis based on production functions, (2) dynamic simulation of production processes, (3) economic decision analysis linked to biophysical simulation, (4) decision support systems, (5) expert systems, and (6) simulation-aided discussions about management in an action research paradigm. Biophysical simulation modelling features prominently in this list of approaches and considerable progress has been made in both the scope and predictive power of the modelling tools. We illustrate some more recent advances in increasing model comprehensiveness in simulating farm production systems via reference to our own group's work with the Agricultural Production Systems Simulator (APSIM). Two case studies are discussed, one with broad-scale commercial agriculture in north-eastern Australia and the other with resource poor smallholder farmers in Africa. We conclude by considering future directions for systems analysis efforts directed at farming systems. We see the major challenges and opportunities lying at the interface of 'hard', scientific approaches to the analysis of biophysical systems and 'soft', approaches to intervention in social management systems.

Keywords: Farming systems; Modelling; Decision support; DSS; FARMSCAPE; APSIM

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1. Introduction

Models of production processes in crop and animal sciences are no longer novelties. The relative ease with which the response in production to an action or an event can be simulated, as opposed to described empirically, has long made such tools conceptually very attractive for aiding agricultural development. But, after more than almost four decades of agricultural modelling a good case can be made that the pursuit of agricultural systems analysis and simulation as a means of expediting application of agricultural research and development is sustained mainly by its perceived *potential*. A factor operating to sustain this perception is substantial progress in tools and methods for analysis in recent years. The aim of this paper is to outline some of these developments and illustrate their application in two contrasting situations, namely commercial agriculture in Australia and small holder agriculture in southern Africa. The subsidiary aim is to place these developments in the context of almost 40 years of agricultural modelling, and to consider ways that the potential of farming systems analysis and intervention might be expedited.

The field of crop modelling seems be experiencing a type of crisis that has been well reported in other such fields. A statistic from the 1999 American Society of Agronomy national meetings in Salt Lake City might be interpreted as indication of our 'crisis'. In the only session on 'Model Applications', of the 10 papers, only three actually concerned applications. More broadly symptomatic is that in spite of technical advances in better models and software over a long period, the success in *problem solving* envisioned by the profession for this technology is disappointing, mainly because it is not used by those who were expected to use it (Seligman, 1990; Ascough and Deer-Ascough, 1994; Parker, 1999). Numerous explanations have been proposed, some agro-technical and others socio-economic; to others it is complex beyond explanation. By analogy with other such 'Technological Programs' (Schon, 1983), realization of the perceived potential to farming of formal systems analysis has been slow due to the underestimated complexity, uncertainty, instability, and uniqueness of farms and increasingly by value conflicts concerning farming within the community. The same problems were also experienced somewhat earlier by users of economic models in the Farm Management movement (Malcolm, 1990). A closer look at these problems and approaches to deal with them will be aided by a look at the notion of 'model' and the nature of 'modelling'.

Caws (1988) distinguished between Representational and Operational mental-models: '...the representational model corresponds to the way the individual thinks things are, the operational model corresponds to the way he practically responds or acts'. The key to efficiency in operational models is success in 'getting away with' *simplification* of 'the way things are' in the interests of perceived practicality. While scientists have differed in the way they have represented farming system complexity operationally, differences have been even greater between the ways economists and scientists represent each other's domain in the farming system. Evolutionary advances in operational models over the past 30 years have been the result of progressive discovery of and responding to oversimplifications that produced unacceptable results and this 'trial and elimination of inadequacy' remains a sound basis for continued practical progress. In a following section we briefly trace the evolution of analysis and intervention in terms of the operational models of farming systems which form the basis for recent new developments. This comparison is conducted using a construct which considers the farm as a cybernetic system (Wiener, 1948), with communication and control links between a *Production System* and a *Management System* (Sorrensen and Kristensen, 1992).

Analyses of farming which takes into account production, efficiency, and sustainability can be variously conducted at a range of scales. By adopting the framework of Fig. 1, we are bounding our treatment of farming systems analysis to the unit which the farmer manages (e.g. a field) plus the domain which is physically affected by flows from this management unit. We are loosely defining a farming system as the Production System plus the Management System on a particular farm or similar farms. We recognize that bounding 'farming system' in this way limits analyses of certain important ecological issues. But we judge the more urgent issue to be demonstration of effective analysis of farms that prove valuable to farmer management and, on the strength of its relevance to real farming, to some policy analysis. This judgement is based on two arguments: (1) the field is the real world entity that most readily corresponds to crop and soil research and hence the scale most robustly modelled, and (2) even if certain problems are defined at more aggregate scales, remedial action usually needs to take place at the field scale, and decisions may be aided by simulation of multiple consequences that aid consideration of trade-offs.

2. Evolution of modelling approaches in farming systems

Several authors have provided helpful conceptual models of the farm (Dillon, 1992; Sorrensen and Kristensen, 1992; Dent, 1994). The relatively simple model of Sorrensen and Kristensen, which distinguishes a Production System from a Management System, is sufficiently comprehensive to assist in our review of historical changes in farming systems analysis and intervention (Fig. 1a). This is a classic data flow diagram from the field of structured systems analysis (Jayaratna, 1986). The key aspect is the cybernetic relationship by which the production system is monitored and controlled to achieve management purposes. Intervention is the rationale for analysis, and the focal point for intervention in Fig. 1(a) is 'adjustment'. Analysis is deemed warranted when a decision about 'adjustment' is problematic and intervention might 'help farmers make more rational decisions'. In Fig. 1(b), a scientifically-rational Systems Analysis and Intervention element is introduced — a 'notional system' in the data flow diagram conventions of Jayaratna (1986).

To date, we recognize six types of systems of analysis and intervention having been used in farming systems (Table 1). Type 1, *economic decision analysis*, was underway prior to the advent of farm-competent production simulation models. The strength of this type lay in the fact of the unit of analysis being the whole farm or enterprise. As shown in Table 1, these models treated production as simple, static, mathematical functions of inputs and outputs. This assumed away any stochasticity and any sensitivity to timing in operations. In the late 1960s, some agricultural

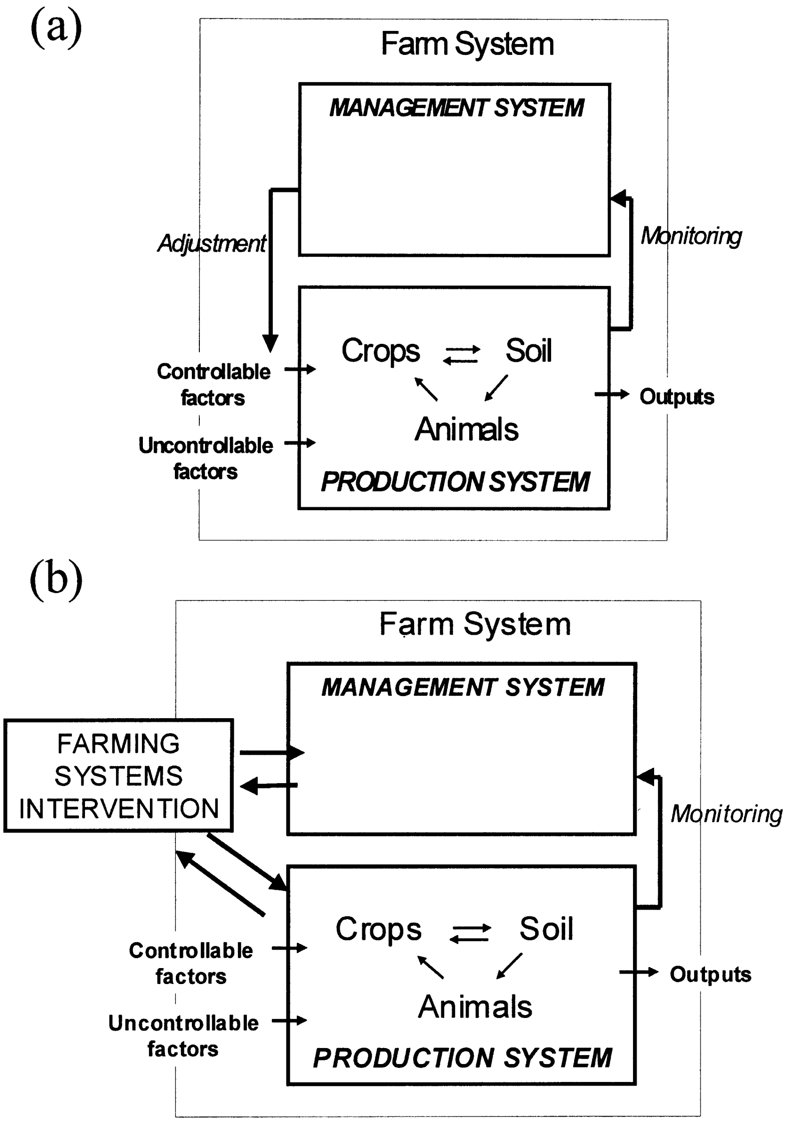

Fig. 1. A 'cybernetic' framework for thinking about a farm as a purposeful, managed system (adapted from Sorrensen and Kristensen, 1992). (a) Highlighting the concepts of monitoring and adjustment linking production and management systems (b) Highlighting the place for a 'Systems Analysis and Intervention' element.

economists saw the advent of *dynamic production models* (Type 2), e.g. crop models, as an opportunity to overcome this deficiency in the way production processes were represented in farm economic models (Anderson and Dent, 1971; Dent and Anderson, 1971; Anderson, 1974). Prominent efforts were sustained on *bio-economic*

Table 1
Approaches to systems analysis and intervention that have been applied to farming systems

	Type of systems analysis/ intervention	Characteristics of systems analysis and intervention	Operational model of production system	Operational model of management system
1	Economic decision analysis using production functions	Recommendations based on whole farm, or enterprise, optimization of production inputs	Static input–output transformations	Suite of notional decision problems
				Categorized initial conditions for economic model
2	Dynamic simulation of production processes	Recommendations based on pseudo-optimization of simulations	Dynamic model of production processes	Suite of notional technical problems
			Categorized initial conditions for simulation	Socio-economic ‘filter’ of technical recommendations
3	Economic decision analysis using dynamic simulation of production processes	Enhanced recommendations based on optimization of production inputs	Dynamic model of production processes	Suite of notional decision problem
				Categorized initial conditions for economic model
4	Decision support system	Decision support system on farmer’s computer	Dynamic model of production processes	Source of notional problem
				User of decision aids
5	Expert system	Recommendations management actions based on conditional rules	Table of action–outcomes	‘If…, then…’ model of expert manager
				User of decision aids
6	Simulation-aided discussions about management	Localized simulation by intermediary in response to farmer’s felt problems as input to farmer learning and decision making	Dynamic model of production processes	Farmer as rational manager with cognitive limits and continuing learning ‘needs’

modelling (Type 3) for most of 20 years (and optimism for much of this period), by Dent and his students (Blackie and Dent, 1974; Dent, 1975; Thornton and Dent, 1984a, 1984b). Of particular interest today, in the light of recent developments in model use, is the recognition in 1971 by Anderson and Dent, that there existed two major impediments to applying simulation models to actual farming. These were the costs of customization and the costs of validation. Achieving reduction in these costs became a major focus of the research of Dent and his students for the next decade. Blackie and Dent (1974, p. 166) considered two approaches to making simulation in farm management more affordable:

> The cost of developing a simulation model for a particular enterprise can be reduced on a 'per farm' basis by constructing the model in such a manner that it can be used by a number of farms. There are two alternative applications of the approach. The first involves the development of a 'representative' farm or enterprise model which can be used to examine the effects of differing management policies. This type of model is largely confined to examining the implications of major management changes. The results from such models can *not* be applied directly to an individual farm and therefore are unable to provide specific management guidance. The second approach relates to the construction of a 'skeleton' model which represents the logical structure and includes only the basic parameters of the real system. Such a model becomes functional only when 'coupled' with data from an individual farm and, in its 'coupled' state, is unique to that farm. The model must be capable of reflecting both the sequence and timing of feasible decisions in order to reflect individual management policies. Systems may appear similar except with regard to their detail; the model must have the capability to adequately distinguish and mimic all such systems.

These authors opted for the skeleton model. They saw private consultants as important players in generating farm data that formed individual farm information systems and farmers acting to update these systems through low-cost enhancements of their normal monitoring of the production system and the external environment (Fig. 1a). Thus, at the interface between the Production system and the Management system of Fig. 1:

> Continuous comparison of projected targets with the present state of the systems provides a systematic procedure for management control. . .The action taken will depend on the estimated outcomes from the various alternatives (which may be explored using the model) and on the managers preferences (p. 167).

As regards costs of validation, Blackie and Dent (1974) point out, that there are real advantages to skeleton models coupled with information systems vis-à-vis validation of models that simulate the general or hypothetical, and which can be tested only on the basis of *plausibility*.

> By contrast, validation of skeleton models is a more straightforward procedure. The system to be modelled is comparatively small and the interactive

> relationships between the various parts of the systems can be acceptably defined. The model is intended to mimic existing real systems under defined management policies. In this circumstance real system data are available and can be directly compared with the model predictions (p. 168).

In 1975, in a review of systems applications which featured skeleton models and coupled information systems, Dent stated: 'The application of skeleton models for management purposes on individual farms can be confidently expected in the not too distant future.' But, judging from lack of mention by Dent in subsequent reviews, it never happened.

Charlton and Street (1975) took a somewhat different tack. Their complex models of both financial and production aspects of pig and dairy enterprises were burdensome, but 'very much simpler ones would have been incapable of being applied to specific farm problems. . .The complexity of the models arose not from the introduction of sophisticated relationships but from the need to provide detail and adequate flexibility' (p. 262). But the high overheads of their approach led them to conclude:

> Models should be constructed to meet limited, well-defined objectives and there has to be a greater recognition of this need for relative simplicity. There is, in fact, a strong argument for producing less general programmes than the ones which have been described here. By restricting each package to a single specific enterprise or problem, such as, for example, the expansion of a pig fattening herd, many of the problems of providing generality with a single programme would be over come.

This simpler approach was characteristic of the '*decision support system*' (DSS) that had appeared in non-agricultural fields by this time (Little, 1970; Keen, 1975) and were to become prominent in agriculture. But attempts to overcome the conflict between the desirability and the feasibility of using the relatively comprehensive simulation models to assist farm management were far from over.

Doyle (1990) bemoans 'the failure of systems concepts and simulation models to have any practical impact on farming', and found:

> disturbingly, the reasons. . .remain the same as those outlined by Dent (1975) some 15 years ago. In the first place, the failure of systems researchers to liaise with farm decision makers has meant that farmers are rightly suspicious of computer-generated predictions of optimal resource use. In the second place, the preoccupation of systems researchers with model-building rather than application has greatly limited the practical use of most. . .models.

This echoes the critique of Musgrave (1976) as well.

Another type of response to the failure using comprehensive models to deliver the previously envisioned intervention in important aspects of design and planning in farm management (Fig. 1) was the scaling down of aims and expectations to what seemed more achievable.

> The very complexity of biological systems and their susceptibility to unplanned variations make it difficult to design adequate representations of the real world. Nevertheless, the systems approach to analysing processes and resource decisions on farms potentially opens up the prospects of using models as aids to control individual farm processes (Doyle, 1990, p. 108).

Vaguely echoing the earlier quoted call of Charlton and Street (1975), for a less general, problem focused approach, this flagged a class of alternative approaches for using models to intervene in farm management, the DSS. Before considering DSS, we present what could be viewed as an epitaph on Farm Management modelling provided by Malcolm (1990):

> But over time emerged an increasingly commonly-held unease, and occasionally conviction, that these were trails which, if followed, soon led from the complex and difficult whole-farm pastures of plenty to simpler and easier analyses characterized by incomplete and inappropriate disciplinary balances and resulting in work which was not really about farm management.
>
> It may be that both farm management and systems research which manages to generate information about general principles and theory relating to the management of farms is more about research in one of the disciplines involved in the management of farms such as agronomy, agricultural economics, animal science, (rural) sociology psychology, engineering, than it is about farm management. This view has the merit of making explicit the gap which inevitably exists between the findings of research and the management of farms, and reminding researchers that agricultural science and agricultural economics are not directly about farming (p. 49).

The concept for *decision support systems* (Type 4 in Table 1) in the field in which it originated, Management Science, was articulated by Keen (1987):

> [The DSS] meshes human judgement and the power of computer technology in ways that can improve the effectiveness of decision makers, without intruding on their autonomy. Traditional DSS provides a *computerized* [proxy for a] *staff assistant*. The manager's judgement selects alternatives and assesses results. 'What if?' became the cliché of the DSS field (Keen, 1987, p. 257).

In agriculture, an indication of Keen's 'autonomy' was residence of the DSS on the farmer's personal computer. The model of the Production System was engineered around a crop model. To the interventionists, the Management System was notionally the source of the developer-construed farming 'problem'. It was assumed that the Management System of 'modern' farms would naturally be increasingly equipped with such aids to decision making as computer ownership increased.

It has taken some considerable time for it to become clear, but there is now little doubt that decision support systems, as originally conceived, have not generally found a significant place in farm management of even 'progressive' Management

Systems. (Seligman, 1990; Ascough and Deer-Ascough, 1994; Hoag et al., 1999; Parker, 1999). These authors highlight the fact that farmers have not used DSSs that have been available. The reasons for this are not well researched or documented, but Webster (1990) offered an economist's view:

> The DSS adoption problem was the result of a gross oversupply by enthusiastic, commercially-unaccountable, publicly-funded research organizations of a technology which had a potential to benefit only a very small proportion of farms (Webster, 1990).

This economist's view may be a little harsh and may have been developed with the benefit of considerable hindsight. One notable exception to the lack of reflection on the usefulness of DSS is the report of Zadoks (1989) on EPIPRE, a computer based DSS on pest and disease control in wheat in Europe. This ground-breaking DSS effort began in 1976, reached peak impact around 1982–1983, and appears to have fallen away up until 1986 when this report was made. Zadoks (1989) reviews a number of sources of evidence for the impact of EPIPRE in farming practice. The evidence of financial benefits was limited, evidence of environmental benefits in terms of reduced chemical usage stronger, and there was almost universal appreciation of the 'learning effect'. Interestingly, the standard recommendations coming from extension appeared to converge with the recommendations from EPIPRE over a 5-year period. The significant point to note here is while the science behind a crop–pest–weather DSS like EPIPRE may be complex, the management decision is simple — basically to spray or not spray. Even in such a well-defined management situation and decision problem, the benefit of the DSS tool appears to be the learning, not the decision support information itself. Once the lessons have been captured, the tool itself appears to be less important. So while use of EPIPRE may have fallen away, it appears to have still delivered benefit.

In our own emerging analysis, central to explanation of low-adoption is the prevalent view of scientist-developers that the DSS is a way of 'packaging' information or a model that 'should' be useful to managers and that, for development to be justified, this aid must be generally applicable. But it has become clear that the key to a DSS being used is its localized, or situated, in practice (McCown, et al. (2001); Berg, 1997, p. 104). The latter author found in a study of medical DSSs in the United States that only a 'handful' of the hundreds of products available were actually in use. These few had common histories of intimate, intensive co-development by 'tool-makers' and practitioners in a workplace. Painful compromises on both sides resulted in a 'transformed tool in a transformed practice', and use did not spread from the practice situation in which it was produced. Our own experience in using a cropping systems simulator with farmers who own and use computers, even when usefulness of the tool is discovered through intensive interaction, farmer preference is almost always for accessing benefits via a consultant skilled in using the tool rather than farmer use of the software.

Expert Systems (Type 5 in Table 1) have been envisaged as a way of providing the model of the farm Management System generally missing in DSS (Dent, 1994). We will not discuss these further because, (1) in the main, they do not use a process model of the Production System and (2) they suffer from problems of 'lack of fit' to specific real-world management situations leading to non-use except for very narrow 'context-free' technical problems (Jones, 1989).

In spite of a history of minimal achievement of impact on farming, optimism about the potential for models in farm management has remained perennial.

The degree of success of agricultural enterprises depends to a large extent on the quality of tactical decision making in response to a variable and uncertain environment. Tactical decisions are aimed at optimizing management practices in such a way that the objectives of the farmer are achieved as completely as possible. Decision support systems that allow analysis of alternative management could be valuable aids in tactical decision making. Such systems, based on crop growth models, that quantitatively describe the relations between environmental factors and crop performance are useful tools in this respect. However, the dynamic nature of the environment (weather, soil conditions), which often appears difficult to predict, limits the applicability of these models, or at least the margins of uncertainty remain relatively large. Therefore it is, in almost all cases necessary to combine these models with field observations that allow adjustment of the models in the course of the growing season. Combination of these models with optimization techniques should provide the basics for such decision support systems (Van Keulen and Penning de Vries, 1993).

An enlightening history (spanning several centuries) of this 'typical' view of the way models are supposed to aid decision making has been provided by Ulrich (1983). The limited relevance of such 'decisionism' lies in its insistence in treating the social Management System 'objectively'. The final category of systems analysis aimed at intervention (Type 6 in Table 1) in the next section departs from this tradition.

3. Recent progress in analysis

In the light of this long history of perceived high potential but little actual impact of model-based farming systems analysis, no progress can be important if it does not include progress in relevance of analyses to farmer decision makers. This is, or should be, of central importance even when the primary client is a policy analyst; it is hard to conceive of more convincing validation of model-based analysis in the business or public policy arenas than high use and usefulness of the core model in the Management System of actual farms. Although there has been a tendency for modellers conscious of the magnitude of the challenge establishing credibility and relevance with farmers to see 'policy' as an easy option, there is little evidence that this has proved to be the case. Our recent experience confirms that nothing gets the attention of actors in the policy arena more than a model that farmers say 'works'.

In 1990, a group called APSRU (Agricultural Production Systems Research Unit) was set up in Australia that sought to bring together skills in crop and soil modelling from a number of agencies. The expectations of our managers who established the Unit were not unlike many of those expressed in the earlier review. That is, there was great potential for simulation modelling approaches to contribute to improved farming practice and this could be achieved simply by capturing the models within Decision Support Systems. In the remainder of this paper, we report on two of the most significant lessons our team has learned over the last 10 years. Firstly that the simulation models needed to undergo substantial enhancement before they could be considered to have much relevance to complex farming systems (in particular in Australia and Africa where we were working) and secondly, that if we were serious about having impact in 'human affairs' in the world, we had to discover new approaches to using the models with farmer, advisor, and policy clients. On the first issue, the story will centre on our experiences in developing the Agricultural Production Systems Simulator — APSIM (McCown et al., 1996), and on the second issue, experiences in intervention methodologies in Australia and Africa are most relevant.

3.1. Making models more relevant to 'real' Production Systems

While the vision that farming systems simulation would contribute to improved farm management dates from the early 1970s, the tools have had to undergo substantial evolution before such a vision could be seriously contemplated. Some key elements of this evolution are suggested in Table 2. The trend has been for greater scope in the issues the simulation model can address and greater sophistication in the software engineering.

APSIM is a modelling framework that allows individual modules of key components of the farming system (defined by model developer and selected by model user) to be 'plugged in' (McCown et al., 1996). Further information on the modular design of APSIM can be found in Jones et al. (2001). When developing APSIM we had the advantage of reviewing the experiences of other groups that carried out their major development efforts in the 1980s. We recognized the strength of models like CERES and GRO (Jones and Kiniry, 1986; Godwin and Singh, 1998; Ritchie, 1998; Ritchie et al., 1998) (that were linked together subsequently in the DSSAT shell [Jones et al., 1998]) in simulating crop yield in relation to management factors. We also recognized the weaknesses in these models in adequately dealing with important 'systems' aspects of cropping. These aspects included dealing with rotations, fallows, residues, crop establishment, crop death, dynamic management decisions that were responsive to weather or soil conditions, longer term soil processes such as loss or organic matter, soil erosion, structural degradation, soil acidification and so on. We were also familiar with simulators, such as NTRM (Shaffer et al., 1983), CENTURY (Parton et al., 1987) and EPIC (Williams, 1983) and recognized the strengths of these models in dealing with the fate of the soil resources in the long-term but recognized the limited sensitivity of their generic crop models to weather input (Steiner et al., 1987). APSIM was designed at the outset as a farming systems simulator that sought to combine climate risk analysis, which requires sensitivity of yield to weather extremes, with prediction of the long-term consequences of farming practice on the soil resource (e.g. soil organic matter dynamics, erosion, acidification, etc.). Some key capabilities that are included in APSIM and are necessary to

Table 2
Some key developments in farming systems simulation over the past 20 years

1980–1985	• Comprehensive crop simulators becoming available (e.g. Wageningen models, CERES, GRO models) • First generation systems simulators becoming available (e.g. NTRM, EPIC)
1985–1990	• Widespread training and usage of these models • Integrated applications 'packages' e.g. DSSAT • Advances in simulation of long-term soil processes (e.g. CENTURY) • Limitations of stand-alone crop models in *farming systems applications* becoming obvious
1990–1995	• Greater capability to address 'systems' issues appearing (e.g. APSIM, later revisions of DSSAT) • Growing recognition of the need for improved software engineering procedures to successfully develop and maintain comprehensive 'systems' models • Optimistic application to farming systems analyses
1995–2000	• Continuing development of bio-physical simulation tools (new modules, new utilities, better designs) • Greater questioning of impact

simulate farming systems (over and above crop and soil process models) are listed in Table 3.

Looking back over the last 10 years of APSIM development and use, the critical elements of the development team's approach that have lead to significant advance in farming *systems* simulation have been:

1. Investment in the good software engineering process, including basic design principles, version control, regression testing, documentation, change and defect reporting.
2. A 'modular' view of model development that sought to cluster related processes in semi-autonomous components or 'modules', to avoid duplication of equivalent function and to enable clear and explicit communications between modules.
3. The early recognition that there was no way all the possible management configurations required of the simulator to be explicitly addressed. This was solved by developing a MANAGER module, that enables users to apply some simple concepts of states, events, actions and conditional logic to build complex management systems whose scope goes well beyond anything envisaged by the early developers. (This *inputs* actual or hypothetical *states* of the Management System; it does not in any way *simulate* the Management System.)

3.2. Experiences in model application to the 'Management System'

In parallel with the effort outlined above targeting improved capability to simulate the Production System (Fig. 1), we were also exploring how best to engage the

Table 3
Capabilities needed in simulators of farming systems, over and above that traditionally found in crop models

Issue	APSIM's approach
Tracking of long term changes in soil properties in response to management and weather	• Well-developed modularity with a set of soil modules that communicate with biological and environmental modules. Crops, seasons, and managers come and go, finding the soil in one state and leaving it in another • Inclusion of soil process modules such as EROSION, SOILpH, SOILN and SOILP
Many management decisions are conditional in farming systems, e.g.	A powerful MANAGER module provides the user with a capability to specify conditional management rules, which control the configuration of the farming system being simulated. Key features of the MANAGER include:
• Sowing dates and details depend on rainfall patterns, soil water content, etc. • Fertilization and tillage operations are influenced by weather, results of soil tests, status of crops, etc. • Crop choice may be influenced by soil water or soil nitrogen levels, prior crop history, etc.	• Conditional rules built up with IF, THEN, ELSEIF, OR, AND, ENDIF operators • Rules can use any state variables made available by other modules • Local MANAGER variables can be calculated using full range of mathematical functions • MANAGER variables can be used in conditional rules and output
Crop and pasture residues need to be left behind on the soil surface at user defined times	A single RESIDUE module receives information on residues from multiple crop or pasture modules and simulates the fate of these residues in relation to weather, soil properties and tillage management
Simulation of crop rotations, relay cropping and intercropping	Crop rotations involving multiple crops, pastures and fallow periods are specified in the MANAGER. More than one crop at a time can be present in the simulation and competition for light and below ground resources simulated via the CANOPY module that simulates light capture in mixed canopies and arbitrates on below ground competition for water and nutrients
Integration of additional information in the simulation	A generalized INPUT module that can input either continuous or discontinuous time series data on any user-defined variable. Uses in farming systems simulation include: • The inclusion of Southern Oscillation Index (SOI) in a simulation to conditionally change management

(Table continued on next page)

Table 3 (*continued*)

Issue	APSIM's approach
	• The input of observed data in the process of model testing • The inclusion of historical data on river flows for use in decision rules for availability of irrigation waters
Simulation of spatially variable systems (e.g. multiple paddocks, agroforestry, windbreaks, alley cropping, farm dams, effluent irrigation systems, water harvesting, precision agriculture, etc.)	Capability currently under development in APSIM. Requires the software system to support instantiation (this is currently possible with FORTRAN90 in APSIM) and requires explicit definition of spatial relationships and processes that operate between spatial units
Inclusion of animal grazing in the simulation	Capability currently under development in APSIM. Requires 'multi-paddock' capability (see above) and links with pasture/grazing/animal production models

Management System. Two examples are provided. One concerns farmers and their advisors in Australia's north-east dryland cropping zone, the other resource-poor farmers in semi-arid Zimbabwe.

3.2.1. Farmers and advisers in Australia's north-east dryland cropping zone

The FARMSCAPE approach (Fig. 2) best captures these experiences and insights (Hochman, 2000; McCown et al., 1998). The FARMSCAPE acronym refers to the actors, Farmers, Advisors and Researchers, involved in Monitoring, Simulation and Communication, and Applying Participative Evaluation.

In the underpinning theory for FARMSCAPE, activities in the 'real' world (e.g. farmers producing crops; Upper section of Fig. 2) are distinguished from 'systems analysis' involving researchers (Lower section of Fig. 2). Fig. 2 also further distinguishes between hard scientific and soft, social processes.

This approach to analysis and intervention (Table 1, Type 6) begins (Fig. 2(a) 1,2) with discussions and negotiations amongst one or more farmers, advisers, and the researchers concerning (1) problems, from the farmer's perspective, of managing crops and croplands in such an environment, (2) the tractability of the problems relative to the skills, tools, and time available for investigation, and (3) a course of action. Without exception, initial interest of farmers has been primarily in co-operative study of a commercial crop, with or without imposing experimental treatments of interest to the farmer (Fig. 2(a) 3). Either way, the most appreciated *field* activity has been the monitoring of soil water and nitrogen as a guide to management actions, to explain crop performance, and to learn about the crop–soil system.

Although, the possible potential of the simulator (Fig. 2(a) 4) to contribute was always raised by the researchers early in discussions, the characteristic response of the farmer is 'I don't mind if you use it, but I can't see how it can help me' — a

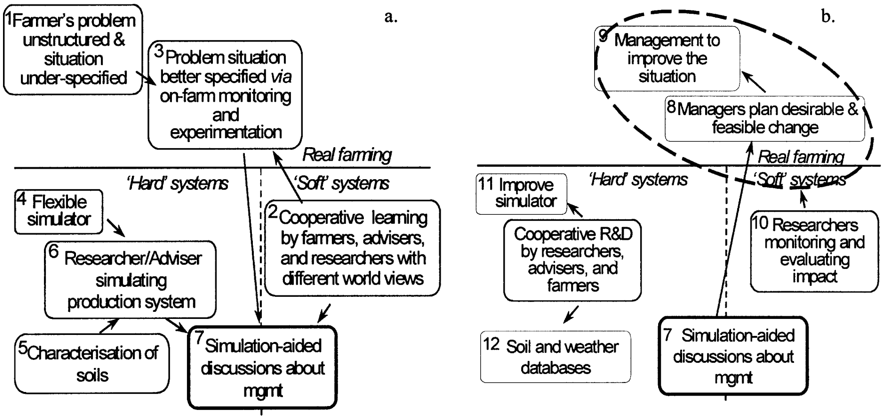

Fig. 2. A model of the FARMSCAPE methodology (a) and (b) are sequential, linked by step 7). After McCown et al., 1998.

response which relegates system simulation to the back burner for a time. But the inevitable problem of applying learning gained from any brief experiment or experience in a highly variable climate always provides an opportunity to re-introduce simulation as a way to get a 'prolonged experience' quickly. Elements of the typical conversation are: 'How would results have differed if we had done the study last year? We can simulate the experiment using last year's weather, but to test if the simulation should be taken seriously, let's first see how well the model simulates the results we just obtained.' This initiates a process in which the respect for the simulator that is required in order for this tool to aid discussions about management (Fig. 2(a) 7) progressively displaces initial scepticism. Our experience is that most farmers are unwilling to engage in this until the credibility of the simulator is demonstrated to their satisfaction (Foale and Carberry (1996) for aggregate performance of APSIM in a farm context).

The simulation-aided discussion about management (Fig. 2(a) 7) is at the heart of this methodology. With a simulator which can reliably predict the consequences of management actions and strategies for the range of weather conditions represented in historical records, very practical experiments for periods of decades can be 'conducted' during the discussion in response to participants' 'what if ...?' questions. These naturally begin as extensions of the field studies (Fig. 2(a) 3), where soil and weather data are being measured and valued in their own right. The addition of soil water storage characteristics of the specific soil (Fig. 2(a) 5) makes possible a highly specific representation of the paddock and the conduct of a wide range of virtual experiments spanning all the years for which rainfall records are available.

Following the 'kitchen table session' (so named for the prevalent location and intimate atmosphere of such farm discussions) participants go back into their real worlds to plan and act (Fig. 2(b) 8,9). Fundamental to any assessment of this approach is the degree to which managers' intentions and actions are affected by the interactions, and monitoring and evaluation of this is a discrete and methodical soft systems activity (Fig. 2(b) 10).

An on-going hard systems activity is improvement of the simulator (Fig. 2(b) 11). Contrary to most expectations this is very much a joint activity. While the researchers look after the scientific modules, the achievement of a high degree of realism in representing the management 'rules' of individual farmers is attributable to (and claimed by) farmers. In addition, there is an ongoing soil characterization and data base development program, with tasks shared among farmers, advisers, and researchers (Fig. 2(b) 12).

Changes in management may give rise to questions that may be addressed either in the field (Fig. 2(a) 1) or in simulation-aided discussions (Fig. 2(a) 7), thereby initiating another cycle of inquiry. The approach has proved highly effective in generating insights about complex management issues made more difficult by a highly variable climate. This appears to be true even for experienced farmers, who would be expected to be well attuned to this climate variability. It has provided researchers with a way of learning about 'what counts' in delivering effective decision support.

The costs are high with this level of researcher–farmer interaction, and the focus of the work has moved to cost-effective delivery options. These centre on use of the agribusiness adviser network, and the group are currently involved in a program, aimed at training (via a formal accreditation process) and providing technical backstopping for agribusiness companies interested in delivering this service as part of their overall business strategy.

4. Resource poor farmers in semi-arid Africa

The story of model application to farm management issues for resource poor farmers continues to unfold. The prevailing sentiment is one of little impact (R. Matthews, personal communication, 1999), but the issue is worthy of a more detailed analysis. Our experience with model application to smallholder African agriculture began in Kenya in 1985 (Keating et al., 1991; McCown et al., 1992) and has continued in different settings until the present day. Currently our focus is on working with ICRISAT and CIMMYT and their collaborators from national agricultural research services on soil fertility issues in climatically risky environments (Keating et al., 1999; Shamudzarira et al., 1999; Robertson et al., 2000, Vaughan and Shamudzarira, 2000).

Our experience with farming systems modelling in Africa mirrors the two major themes that run through this paper. Development of models that were relevant to the Production Systems (Fig. 1) of low-input farming in Africa dominated the early years. The crop–soil models available in 1985 were better suited to high-input commercial agriculture than smallholder farms in Africa. Issues needing to be addressed included crop establishment failure, low plant populations, crop death due to extreme stresses, weed impacts, tactical management responses to variable climate, non-nitrogen soil fertility constraints (e.g. phosphorus), alternative soil fertility amendments (e.g. residues, manures), etc. In more recent years, the focus has shifted to effective intervention strategies in the Management System and the role for farming systems models in such interventions.

The journey we have travelled with farming systems models in Africa is best illustrated with a few examples of analyses that have been undertaken and what was done with these analyses. Fig. 3 captures much of what was achieved with the farming systems models in Kenya over the 1985–1991 period. It comes from Keating et al. (1991) and shows output from the CM–Ken model, an adaptation of CERES-Maize (Jones and Kiniry, 1996). The model was specified for a scenario that approximated farmer practice in Machakos, in semi-arid eastern Kenya (Step 1). A series of alternate scenarios were developed that represented increasing investment in the Production System (Steps 2–4). The key variables were fertilizer inputs, residue retention on the soil surface and plant population.

Step 1 is a scenario that approximates the current system. Runoff is high (mean 62 mm per season) and organic carbon is low (0.9% in the surface), plant population is low (1.6 plants m^{-2}), no N fertilizer, and no crop residues are returned to the field. Mean grain yields of 970 kg ha^{-1} were on the upper side of the averages reported in the region, likely because losses due to poor management such as delayed planting, weeds, pests, etc. have not been simulated.

Step 2 represents a first step towards a better system. It involves adding 10 kg N ha^{-1}, increasing plant populations to 2.2 plants m^{-2} and returning the 'extra' stover produced to the field as surface mulch, with resulting benefits in terms of reduced runoff and soil evaporation. Mean grain yields of 1830 kg ha^{-1} were simulated for this scenario.

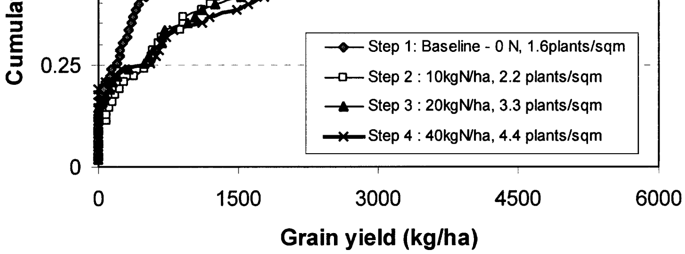

Fig. 3. Cumulative distribution function for gross margin associated with four steps in a proposed development pathway (after Keating et al., 1991). See text for detail of Steps 1–4.

Step 3 involved further increases in plant population (3.3 plants m^{-2}) and N fertilizer (20 kg N ha^{-1}) and the assumed benefits of returning the extra stover. Mean grain yield of 2300 kg ha^{-1} was simulated.
Step 4 combined 40 kg N ha^{-1} with a plant population of 4.4 plants m^{-2}. The extra stover produced was assumed to be returned to the soil surface. The mean grain yields of 2740 kg ha^{-1} simulated in this scenario can be viewed as a production potential with excellent management.

Fig. 4 illustrates more contemporary analyses. This comes from work with CIMMYT and ICRISAT and NARS partners in Zimbabwe (Keating et al., 2000). The starting point for the modelling analysis was a defined level of land, labour and cash resources, that were relevant to smallholder circumstances in a particular region of Zimbabwe. The cash could be used to purchase fertilizer or labour related services such as early ploughing or more timely weeding. Four fields were simulated (for simplicity each assumed to be 1 ha) in Natural Region II, using the 1951–1991 weather record for Harare, and model outputs aggregated to a whole farm level. APSIM was used as the modelling tool, configured to track short- and long-term crop–soil processes, and to address competition for water and N between crops and weeds. The six scenarios explored were:

Scenario 1 was based on extension advisers' views of what would constitute good practice. Fields were sown progressively from 15 October to 10 December to reflect the labour and oxen constraint. Two bags of ammonium nitrate (AN) fertilizer was used as a split side dressing (35 kg N ha^{-1}) was used on each of Fields 1 and 2, and there was sufficient labour to weed these fields. Fields 3 and 4 were unfertilized and unweeded.
Scenario 2 was termed the 'concentration strategy'. Fields 3 and 4 were not planted and the resources freed up, assumed to be converted to cash (e.g. through

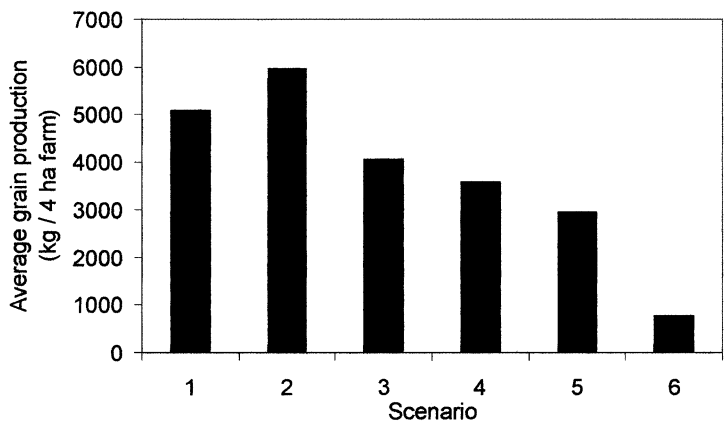

Fig. 4. Average grain production for the six scenarios explored in Natural Region II in Zimbabwe, expressed in terms of grain produced from the whole farm (with 4 ha of cropping) per year. After: Keating et al., 2000.

sale of labour elsewhere in the district) and used to purchase extra fertilizer (52.5 kg N ha^{-1} on Fields 1 and 2).

Scenario 3 was termed the 'spreading strategy'. It was set up in a similar fashion to Scenario 1, except the fertilizer was spread at the same rate (17.5 kg N ha^{-1}) over all fields.

Scenario 4 involved investing in more timely weeding in lieu of additional N fertilizer (e.g. as for Scenario 1 but 35 kg N fertilizer applied to Field 2 only and all fields weeded).

Scenario 5 involved investing in early land preparation and sowing in lieu of additional N fertilizer (e.g. as for Scenario 1 but 35 kg N fertilizer applied to Field 2 only and all fields planted prior to 5th November each year).

Scenario 6 was included to capture a poor management situation where severe labour constraints meant that all fields were sown late (mid December) and not weeded. Only Field 1 received any fertilizer.

These analyses highlight the importance of matching investments in fertilizer with other optimal agronomic practices, such as early establishment and good weed control. They have helped the researchers to appreciate the trade-offs on farms between financial resources and labour availability. In more recent times, this type of model output has been taken back to farmer groups and used as a basis for discussions about constraints to productivity on farms. This has not been done in terms of the tables and graphs that researchers are familiar with, but in terms of the units of measures that farmers think of (e.g. bags and ox-carts of grain from different fields). While this approach is in its infancy in smallholder circumstances, the experience to date has been that it can enrich the interaction between farmers, extension personnel and researchers.

There are very significant differences in the comprehensive of the analyses that were or could be done in 1990 and in 2000. The earlier work considered only one crop, one nutrient (nitrogen), ignored weeds, did not consider soil degradation through erosion, and gave only limited consideration to the resource constraints that operate on smallholder farms in Africa (the work implicitly recognized that cash for fertilizer inputs and crop residues were limited resources subject to competing demands). The longer-term changes in soil resources, such as C/N dynamics and soil erosion were not considered in the analysis. The more recent work was structured around the notion of some limited resources available on a farm and explored alternative ways in which these resources might be used. It recognized that labour and/or cash were limited and had to support land preparation/planting, weeding and fertilizer inputs. While the scenarios shown here considered only maize, the models are capable of simulating a diverse range of crops and forages in rotations or mixtures. The more recent analyses recognized that different fields had to be planted at different times, on account of limitations in labour and/or cash for ploughing and weeding. They explored trading off one resource investment for another (e.g. instead of buying fertilizer, use the resources for better weeding or earlier land preparation and sowing). They examined different options of spreading or concentrating the different resources on the farm. Clearly there has been substantial advance in the degree to which the modelling analyses can be specified in ways relevant to smallholder farmers in strongly resource constrained situations.

A more important difference between what was being done with the models in the 1980s and what is being done now is in how the output of these modelling exercises were or are being put to use. The Kenya work was reported in scientific meetings and papers and if it had any real impact, it was on the attitudes of other researchers and those that invest in research. It was not taken to real world practitioners in any systematic or substantive way. Current modelling analyses in southern Africa are linked in with participative research activities, whereby farmers, advisers and researchers interact; (1) to specify the models in ways that are realistic to farmer circumstances and (2) to explore the outputs of the modelling studies back on the farm with farmers. These latter activities are posing new challenges of how to communicate model outputs in simple ways that have meaning to farmers. The need to link model assessment of production practices and technology options with farmer-led experimentation is also apparent in the smallholder situation in Africa, something that is consistent with the experience in Australia with commercial farmers.

5. Future directions in farming systems analysis

Looking forward, we see continued increases in capability to simulate the biophysical performance of production systems that is matched by an increase of involvement in improving system performance.

This greater modelling capability will come via consideration of a wider range of the factors determining system performance and in better predictive/explanatory skill in the sub-models used. Advances in computing power and in utility of programming languages will contribute to this enhanced capability. Predicting the functionality of computers and digital communications in 20 years time is as difficult as it would have been to anticipate the exponential advances made over the last 20 years. All we can assume is that the changes will be beyond our wildest imagination. We see greater attention to 'space' within farming systems simulators, to compliment the focus on temporal analysis that have been dominant to date. This will in part be driven by greater emphasis on issues of sustainable farming practice and agricultural practices in better harmony with natural ecosystems. Issues such as mixed farming, precision agriculture, mosaic farming, farm forestry and other combinations of trees and crops will require more sophisticated analysis tools that are cognizant of the spatial relationships of system components. Issues such as farm-scale water capture, storage, transfer and use have strong spatial and temporal elements that benefit from farm and paddock scale model applications. Lisson et al. (2000) provide an example of how paddock scale crop–soil models can be elaborated to provide insights into these more complex water management issues in the farming system. We also see greater attention to the 'non-production' aspects of farming systems models. The existing strong demand for models to address the fate of the soil resource (organic matter cycling, soil acidification) and wider questions of sustainable agriculture (dryland salinity, erosion, greenhouse gas emissions) will intensify [Probert and Keating (2000) for a review of related matters].

While we see technical opportunities for the comprehensiveness of biophysical simulation tools to evolve, justification and support will depend on demonstrable benefit of existing capabilities to 'real agriculture'. The vision has existed since the 1970s that management models would become indispensable tools in farm management. Such models would be capable of customization to mimic the reality of individual farms (e.g. the 'skeleton model' concept of Blackie and Dent, 1974) and that optimization would be a powerful tool to identify 'best' practices and decisions (e.g. Van Keulen and Penning deVries, 1993). We have seen great enthusiasm for 'packaging' 'ideal' information and recommendations derived from models or implicit in imbedded models as Decision Support and Expert Systems as a way of reaching real farmers but far too little critical evaluation of use or usefulness of such tools. Clearly the visions of the 1970s have not been reached and after 30 years of effort, there is a need for greater questioning of the basic principles underlying our attempts to connect a hard systems view of Production Systems (encapsulated in simulation models) with the human dimension of Management Systems (Fig. 1).

The 'action research' principles (Argyris et al., 1985; Schon, 1983) used in the FARMSCAPE activity appear to be relevant to more effective links between our science (and farming systems analysis tools) and farm management practice. In our own group's work, the focus is on the learning experience that accompanies the interaction of research (including the modelling tools) and farm management practice. The fact that learning is two way makes it a more modest endeavor than the notion which permeates DSS developments that science is 'providing the answers for management'.

Without demonstrable relevance and significance to farming practice it is hard to see how model-based decision support can avoid a continued slow demise. But if through reformed research practice a new credibility can be achieved, opportunities exist beyond farmer decision support. Whilst acknowledging that the record for farming systems analysis and modelling engaged in normative policy analyses is disappointing, we see a continuing need for a relevant and competent input. The clients for such policy research are not just government policy makers, but also others who are making decisions everyday about the allocation of scarce resources and interpretation of data, whether they be research managers assessing research directions and implications, land management agencies reflection on their portfolio of investments, agribusiness companies scoping new business opportunities or government agencies developing and/or implementing their programs.

While important challenges and opportunities exist in model development, the biggest challenge facing the practitioners of farming systems modelling over the next 10 years, is not to build more accurate or more comprehensive models, but to discover new ways of achieving relevance to real world decision making and management practice. We judge that failure to meet this challenge constitutes a major threat to the entire farming systems modelling enterprise. We believe that conversion of this threat to an opportunity will require not so much improving the quality of our research as in changing the way we do research. Comfort for continuation of a cherished research tradition can no longer be found in an old dichotomy of research and extension. Not only do we see agricultural extension disappearing, but we see research being redefined in terms of social value and broader social involvement. For example:

> Two knowledge producing systems — Mode 1 [traditional science] and Mode 2 [science which engages clients] — currently coexist. The key question is whether the current coexistence will last. Many academic scientists still hope that the [recent] changes. . .have had a limited impact and that the number of actors who have the been drawn into [Mode 2] knowledge production is still comparatively small. Our view. . . is that the present changes in knowledge production are too profound and multifaceted to make this a realistic expectation. We believe that Mode 1 will become incorporated within the larger system which we have called Mode 2. . .. (Gibbons et al., 1994, p. 154).

Not surprisingly, the role of modelling in this new mode of research is seen as central (p. 45) but emphasis is on 'usefulness' as a success criterion (p. 18). While, this is one among many ways of conceptualizing and discussing the changes taking place in our research environment, it is clear to us that such change is indeed well advanced in many agricultural research environments. We are trying to grasp the opportunities that this change provides for farming system analysis.

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