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Increasing profits and reducing risks in crop production using participatory systems simulation approaches

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Abstract

The development of cropping systems simulation capabilities world-wide combined with easy access to powerful computing has resulted in a plethora of agricultural models and consequently, model applications. Nonetheless, the scientific credibility of such applications and their relevance to farming practice is still being questioned. Our objective in this paper is to highlight some of the model applications from which benefits for farmers were or could be obtained via changed agricultural practice or policy. Changed on-farm practice due to the direct contribution of modelling, while keenly sought after, may in some cases be less achievable than a contribution via agricultural policies. This paper is intended to give some guidance for future model applications. It is not a comprehensive review of model applications, nor is it intended to discuss modelling in the context of social science or extension policy. Rather, we take snapshots around the globe to 'take stock' and to demonstrate that well-defined financial and environmental benefits can be obtained on-farm from the use of models. We highlight the importance of 'relevance' and hence the importance of true partnerships between all stakeholders (farmer, scientists, advisers) for the successful development and adoption of simulation approaches. Specifically, we address some key points that are essential for successful

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model applications such as: (1) issues to be addressed must be neither trivial nor obvious; (2) a modelling approach must reduce complexity rather than proliferate choices in order to aid the decision-making process; (3) the cropping systems must be sufficiently flexible to allow management interventions based on insights gained from models. The pro and cons of normative approaches (e.g. decision support software that can reach a wide audience quickly but are often poorly contextualized for any individual client) versus model applications within the context of an individual client's situation will also be discussed. We suggest that a tandem approach is necessary whereby the latter is used in the early stages of model application for confidence building amongst client groups. This paper focuses on five specific regions that differ fundamentally in terms of environment and socio-economic structure and hence in their requirements for successful model applications. Specifically, we will give examples from Australia and South America (high climatic variability, large areas, low input, technologically advanced); Africa (high climatic variability, small areas, low input, subsistence agriculture); India (high climatic variability, small areas, medium level inputs, technologically progressing; and Europe (relatively low climatic variability, small areas, high input, technologically advanced). The contrast between Australia and Europe will further demonstrate how successful model applications are strongly influenced by the policy framework within which producers operate. We suggest that this might eventually lead to better adoption of fully integrated systems approaches and result in the development of resilient farming systems that are in tune with current climatic conditions and are adaptable to biophysical and socio-economic variability and change.

Keywords: Systems approach; Modelling; Farmer interactions; Climate; Management

1. Introduction

Analyzing agricultural systems and their alternative management options experimentally in real time is generally not feasible because of the length of time and amount of resources required. For instance, to sample the effects of climatic variability and associated management responses adequately may require many decades of experimentation, particularly in areas where such variability is high. Alternatively, well-tested simulation approaches offer a time and cost-efficient alternative to experimentation on the physical system and results can be obtained in hours or days rather than years or decades (Keating and McCown, 2001). Today, simulation analyses have become a legitimate means of evaluating policy and resource management issues (Netherlands Scientific Council for Government Policy, 1992; Nelson et al., 1998a, b; Silburn and Connolly, 1998; Howden et al., 1999). The concept of systems dynamics evolved over a century ago with pioneers such as Justus von Liebig, Albrecht Thaer and Carl von Wulffen. Their work led to a realization of the interdependence of variables in agricultural systems and to an understanding of nutrient cycling depending on the three production parameters: quantity, intensity and efficiency (De Wit, 1990). The advent of crop physiological models, implemented on computers, can be traced back to some ground-breaking work in the 1950s, such as Monsi and Saeki's (1953) paper on light interception and De Wit's (1958) paper on transpiration and crop yields that also draws on some of Penman's early work (Penman, 1948). These and similar publications constructed the framework for the emerging formalism of systems analysis (Zadoks and Rabbinge, 1985). Phrasing physiological processes in mathematical terms allowed us for the first time to quantify biophysical consequences of environmental variability. This led to today's proliferation of computer simulation models such as DSSAT, SUCROS and APSIM (IBSNAT, 1990; Goudriaan and Van Laar, 1994; McCown et al., 1996).

In addition to their use as systems analytical tools, simulation approaches are often proposed as efficient tools to assist farmers' decision making. Just as often, the implementation of these approaches are criticized as either inappropriate, ineffective or failures (Plant, 1997). This criticism mainly relates to the lack of adoption by farmers of the countless decision support systems (DSS) that have been developed in recent decades (in this context the term DSS is used in its widest sense and refers to all 'normative' approaches of simulation based information provision, including software products and dissemination of such information via printed or Web-based media). Examples of this debate within the context of social science and extension policy can be found in McCown et al. (1994) and Cox (1996).

Rather than adding to this debate, we intend to present some examples from around the globe where farmers have benefited or are likely to benefit from a simulation approach. Client involvement is generally recognized as an important step in the process of adoption of new technologies (e.g. fertilizer application, Wahbi et al., 1994). This also applies to simulation technologies in all their various forms (Hamilton et al., 1991). Ignoring this fact is likely a major contributor to the failing of adoption of many DSS. The form that client involvement can take depends strongly on the physical and socio-economic environment within which the research is to be conducted. It is our intention to demonstrate that simulation approaches are most effective when conducted through direct involvement of the decision makers.

We can identify two categories of how simulation results may influence farmers' decisions:

1. directly, by providing necessary background information about the likely outcome of a decision and associated risks; and
2. indirectly, by changing the policy framework which in turn will then influence decisions on farms.

Regardless of category, the degree to which farmers are influenced in their decision making is difficult to measure and firm evidence in the literature is rare. In case of the former category, scientists tend to publish the theoretical principles that are aligned with but not directly related to real life problems. Direct intervention with decision makers is largely regarded as extension and as having low scientific value. Evaluation of the success and impact of any intervention is not often undertaken and even more rarely reported in the literature. Most of the simulation efforts concentrate on possible new research projects, on the research necessary to develop explanatory models or on the scientific aspects of the applications (Bowen et al., 1995; Ten Berge et al., 1997). Evidence of actual farmer actions or reactions to simulation approaches are rare (Meinke and Hochman, 2000). There are ample examples of analyses of possible policy decisions, but again this is rarely followed up with a thorough assessment of policy changes caused by these analyses and their subsequent impact on farmers' decision making.

Inevitably, farmers make decisions under uncertainty. By providing new information about the environment within which they operate or about the likely outcome of alternative management options, this uncertainty can be reduced (Byerlee and Anderson, 1982). Computer simulations can provide such information and are particularly useful to quantitatively compare alternative management options in areas where seasonal climatic variability is high, such as Australia, South-east Asia, Africa and South America (Keating and Meinke, 1998; O'Meagher et al., 1998; White et al., 1998). Simulations not only allow assessment of the effects of management options on production, but also enable the evaluation of associated impacts on the resource base such as runoff, erosion, nutrient leaching and pesticide movement (Silburn and Connolly, 1998; Carberry et al., 2000). Hence, there is increasing interest in using a simulation approach in situations where development of appropriate environmental guidelines is of greater concern than production per se (e.g. carbon sequestration). Ten Berge et al. (1997) point out the importance of such regulation and the need for growers to demonstrate compliance, often via a simulation approach.

However, the fact remains that the successful application of models or model output for the benefit of farmers is rare (or at least rarely documented). To be effective, such tools must provide answers that are neither trivial or obvious. In other words, the information provided must at least have the potential to alter a decision. Using a range of case studies, we aim to demonstrate the potential power of simulation tools in improving agricultural practice. In the case of Australia and South America, such benefits can be clearly attributed to simulation approaches and can, at least in some instances, be quantified in terms of increased profitability or production, or reduced environmental risks. In the African and European case studies, the links to real, on-farm benefits are more circumstantial and will require a more co-ordinated effort if the promising potential is to be realized. How this might be achieved is discussed within the context of a current project activity in Asia. The Indian example demonstrates a case where benefits are likely, but successful outcomes will depend on efficiently linking with farmer networks and integrating policymakers into the systems analytical process.

2. Low intensity, technologically advanced cropping systems in drought-prone areas

Crop production in Australia is characterized by technologically advanced producers managing large areas with low intensity against the background of high climatic variability (Pratley, 1994; Meinke and Hammer, 1997). The lack of subsidies combined with low commodity prices requires producers to become increasingly efficient. Modelling approaches are ideally suited to evaluate alternative options in terms of their resource use efficiency. Seasonal forecasting has much to offer by increasing inputs in years that are likely to yield well and reducing inputs when the chances for lower than usual yields are high (Plant, 2000).

Farmers are cognizant of uncertainty and make management decisions with full knowledge that the outcome of these decisions is uncertain. Information about their system combined with past experiences allows a subjective assessment of the likely outcome. Simulation models are increasingly recognized as a valid and important source of such information by a growing number of Australian farmers. The last 10 years have seen a rapid change in farmer perception of the value of agricultural models, at least in those parts of the Australian cropping region where well-targeted simulation output has contributed to farmer led discussions concerning issues of interest to participants (Coutts et al., 1998).

Good farm managers have a rich appreciation of agricultural systems components and their interactions and are skilled at incorporating new information into the decision-making process. In north-eastern Australia a cropping systems approach helps farmers to replace 'gut feeling' about their complex system with (1) hard data about the current state of their system (e.g. soil moisture stored over a fallow) and (2) with probabilistic information about the way in which the unknown (e.g. future in-season rainfall) will affect the outcome of alternative management decisions (Carberry et al., 2000; Meinke and Hochman, 2000).

2.1. Climatic risk

Quantification of climatic risk to evaluate management decisions objectively is an important area for model applications. This approach aims to maximize the profitability of the whole farm operation. When combined with a seasonal climate forecast, impact of the climatic risk can be reduced considerably (Hammer et al., 2001). Keeping in mind that water is often the most limiting resource in this environment, key management responses aim to:

1. avoid erosion and run-off;
2. maximize water infiltration;
3. develop a surface management system that allows sowing a crop after even minor rainfall events in order to be as close as possible to the optimum sowing date; and
4. avoid soil fertility decline.

With the help of dynamic crop simulation models, producers can evaluate alternative management options and quantify the likely effect on farm income and production risk. Using up to 100 years of daily weather records, producers can compare the long-term outcomes of such management decisions in terms of risk and income security. To be effective, this approach requires an understanding of the probabilistic nature of the information provided, whereby producers must not become disheartened or reckless by any perceived 'failure' or 'win' of outcomes achieved in any given season. As with any probabilistic approach, it must be used consistently over a number of seasons to accumulate a net benefit from a management strategy. Further, it must be integrated into the whole decision-making process as one of many management tools.

Meinke and Hochman (2000) showed in their case study that farmers use, for instance, simulated 'target yields' based on simulations to optimize nitrogen strategies. These target yields are determined based on the amount of stored soil moisture prior to sowing, historical rainfall records and the long-term rainfall outlook. From this, they estimate the 10 percentile of achievable yield in a given season. Nitrogen requirements are then determined based on the available background nitrogen in the field and the appropriate amount of nitrogen is applied.

Meinke and Hochman (2000) profiled a grain/cotton grower in the north-eastern Australian wheat belt. Amongst the benefits attributable in part to simulation output were decisions relating to:

1. the under no-till area;
2. the amount of nitrogen fertilizer applied prior to planting;
3. planting dates for wheat to spread frost risk;
4. double cropping barley after cotton (i.e. a winter crop sown straight after a summer crop on very little stored soil moisture; this crop yielded close to 3 t ha^{-1}, a rare yield level for a double crop and only achievable under favourable climatic conditions);
5. choice of alternative crops to wheat in order to spread risk (e.g. wheat versus chickpeas).

This grower's yield and grain quality were substantially above the district average and he partly attributes this positive result to his ability to incorporate simulation output into his decision making.

2.2. Farmer interactions

This intensity of scientist/producer interactions cannot be maintained beyond specific pilot projects. Methods need to be developed that allow the generalization of the knowledge gained by scientists and producers through such intense interaction. Regional diversity makes such generalizations difficult.

One approach is the closer involvement of farmer groups and their advisers in exploring together how simulation may impact on farm decision making (McCown et al., 1998). This research approach aims to explore suitable methods for agribusiness and/or consultants to access relevant simulation results and climate forecast information. In partnership with local agribusiness firms, APSRU has accessed a range of regionally diverse farmer groups for whom simulations have been provided relating to relevant management options. Evaluation of these meetings has shown that they can have significant impact on the way in which farm managers are thinking about and acting on their tactical decisions (Coutts et al., 1998).

Calculating the odds of growing an economically successful crop requires knowledge of the soil type, the amount of stored soil moisture reserves, nitrogen requirements, likely price movement, rainfall and frost outlook. Such information needs to be assessed within the context of tactical, crop-specific management options (sowing date, area sown, nitrogen fertilization strategy, etc.) and more strategic, rotational options (grow an alternative crop, not grow a crop at all). Depending on the issues that farmers bring up in these discussions, simulations are conducted for their specific conditions (provided that inputs such as current amount of soil moisture content, climate records, etc. are available) at that point in time (Carberry and Bange, 1998; Hochman et al., 1998; Robertson et al., 2000; Hammer et al., 2001).

Considerable success within pilot farmer groups has led to a market in northern Australia for timely and high quality interactions based on soil monitoring and simulation amongst a significant sector of the farming community. The demand for simulations has increased rapidly to the point where APSRU and associated public sector extension personnel cannot meet that demand, nor justify providing a 'commercial' delivery service. Rather, the intention is to transfer to agribusiness the capability to deliver, via an Accredited Adviser Network, simulation and related products to farmer clients in the northern cropping region. Grains Industry funding has been obtained to support four agribusiness companies to become accredited and supported in implementing this approach within their business practices.

An alternative, less intensive approach to accessing generalized simulation output is via the 'Whopper Cropper' software product, consisting of a database of pre-run APSIM (Agricultural Production Systems Simulator; McCown et al., 1996) simulations with an easy-to-use graphical interface facilitating time series, probability and diagnostic analyses. It was designed for users to be able to access crop yield simulations without having to learn how to run the more flexible and comprehensive APSIM systems model. We regard it as a discussion support system designed in response to a demand from extension professionals for easy access to cropping systems modelling and seasonal climate forecasting (Hammer et al., 2001). Decision support systems should support, and not replace human judgement. They should amplify the cognitive elements of decision making over the emotive elements by storing, retrieving, processing and reporting information (Keen, 1993; Chang et al., 1994), but allow users to explore and choose solutions using context specific reasoning not easily programmed into a decision support system (Collins, 1992). The needs and preferences of extension professionals have driven the design and development of Whopper Cropper to the extent that current versions bear little resemblance to the researcher generated prototypes used initially to demonstrate the potential of the underlying research (Hammer et al., 2001).

2.3. Influencing drought policy

There is also evidence of simulation modelling influencing decision making in Australia via policy analysis. For instance, the determination of appropriate drought policies and the assessment and declaration of drought exceptional circumstances are issues that require objective information regarding the impact of climate variability on agricultural production. Simulation models allow not only an assessment of the severity and frequency of drought events, but can be used to evaluate management responses that result in a higher level of drought preparation at the farm, regional and institutional level. A wide range of studies have shown how these concepts can be operationalized. In particular, these studies highlighted important differences between 'climatological droughts', 'production droughts' and 'economic droughts' which are rarely synchronized (e.g. Hammer et al., 1996; Hall et al., 1997; De Jager et al., 1998; Donnelly et al., 1998; Keating and Meinke, 1998; O'Meagher et al., 1998; Stafford Smith and McKeon, 1998; Stephens, 1998; White et al., 1998). Combined with the ability for seasonal climate forecasting, this has resulted in a much higher level of drought preparation in Australia, and hence increased the capacity to better absorb negative impacts of drought.

2.4. Climate forecasting and modelling

Similar to Australia, agricultural producers in Uruguay are technologically advanced and have to manage large areas under highly variable rainfall conditions. However, while Australian producers are more likely to suffer from droughts in El Niño type years, their counterparts in Uruguay are likely to encounter excess rainfall in such seasons (and vice versa in La Niña type seasons). The impact of climate variability led to the establishment of pilot programmes that bring together climate scientists, agronomists, crop modellers and farmer representatives. Supported by organizations such as NOAA-OGP (National Oceanic and Atmospheric Administration — Office of Global Programs), IRI (International Research Institute for Climate Prediction, Columbia University, New York), IAI (Inter-American Institute for Global Change Research) and regional association of farmers, these groups participate in the Regional Climate Outlook Fora for south-east South America. Uruguay hosted the first Forum in December 1997, and has continued organizing these fora every 3–4 months. As in Australia, simulations play a crucial role in analyzing management responses to the seasonal climate outlook. For the scientists involved, these fora provide an excellent opportunity to interact, exchange results, discuss methodology, and solicit feedback from producers about the general approach, the methodologies used and additional information needs.

The regional office of IFDC (International Fertilizer Development Centre) in south-east South America works with researchers from INIA (National Agricultural Research Institute, Uruguay) to develop tools for optimizing the use of the climate outlooks. Activities include:

1. Identify crop or pasture systems that have a good 'signal' of ENSO (El Niño-Southern Oscillation), i.e. where the underlying climatic fluctuations translate into associated fluctuations of production (Messina et al., 1999).
2. Identify climate variables that explain a large proportion of the observed production variability (e.g. rainfall around flowering in maize, late frosts in wheat, soil water availability in rangelands). This activity focuses scientists' thinking and triggers further research into subjects that are 'useful' as opposed to subjects that are only 'scientifically interesting'.
3. Use simulation models to explore management practices that can minimize losses or take advantage of favourable conditions associated with expected climate anomalies. Also, use the information to produce crop/pasture productivity forecasts.

4. Introduce these components in the Information and Decision Support Systems currently being developed for the region.

Short workshops are then conducted that include the climate scientists, agricultural researchers and technical representatives of all the major farmer associations and government agricultural planners (Ministry of Agriculture and Fisheries). In these workshops, climate scientists present the outlook from the regional fora, as well as local forecasts which have a higher spatial resolution. The agronomists and modellers then present results on the impact of climate variables on production under a range of different management scenarios (analogous to the Australian 'what if' analyses). They further present novel tools under development for assisting in the decision making and planning. Finally, and most importantly, the technical representatives from the farmer associations critique the agricultural scientists' work by providing feedback and suggesting alterations or modifications for the preliminary analyses conducted. The technical representatives will brief their associations on the final outcome. In addition, short documents for the press are prepared (newspapers, radio and TV). An annual workshop exclusively for the press is held, since that is still the major source of information for the farmers in this region. These workshops are now regarded by participants as one of the most useful activities of the entire programme. Similar activities are taking place in neighbouring Argentina and the regional fora are playing an important role in facilitating cross-border collaboration (Magrin, personal communication, 1999).

3. Environments with relatively low climatic variability, small areas, high input, technologically advanced

Rainfall variability in Europe is, compared with the other case studies presented here, relatively low. Agriculture is dominated by highly productive but relatively small management units and generally features high levels of inputs such as fertilizers, pesticides and herbicides. This leads to considerable environmental pressures and strong demands by the general public to minimize adverse off-site effects of agricultural production (Netherlands Scientific Council for Government Policy, 1992). Consequently, environmental guidelines were required that specify allowable limits for off-site effects and provide a framework for producers defining acceptable and unacceptable management practices. Dynamic simulation approaches could play an important role in such policy formulation by better quantifying these production associated environmental risks, and assisting in the development of management strategies acceptable to both, producers and the wider community. Although many case studies have demonstrated this potential (see later), there is little evidence to date that policy formulation is based or even influenced by dynamic, quantitative approaches.

Many case studies have quantified the environmental risk from non-point source pollution to subterranean water using simulation models (Civita, 1993). Typically, maps quantifying the vulnerability of aquifers are produced (Zavatti et al., 1992).

However, this often represents only a static view of the agricultural system under investigation and does not allow for the dynamic evaluation of interactions resulting from management intervention.

In order to evaluate the possible consequences of different agricultural management practices on the environment, it is essential to develop tools that assist in quantifying the effects of management options on variables of interest. As already discussed, well-tested simulation models for cropping systems allows probabilistic quantification of complex plant/soil/environment interactions that cannot be obtained experimentally (Thornley and Johnson, 1990; Van Evert and Campbell, 1994). Cropping system simulation models in combination with hydrological models can be used to assess the long-term sustainability of management practices (Trevisan et al., 1997; Carberry et al., 2000; Asseng et al., 2001a, b). Such an approach is necessary because experimental data collected in diverse environmental conditions have resulted in diverse conclusions with respect to the potential risk of contamination of groundwater (Grignani et al., 1994; Rossi Pisa, 1995; Sequi et al., 1995). Credible simulation approaches offer a possible solution to overcome this impasse.

In this case study, diverse cropping systems in two areas around Emilia Romagna, Italy, were evaluated using the simulation model CropSyst (Stöckle and Nelson, 1994; Stöckle and Donatelli, 1997). Arc/View software was used to visualize the output produced by the simulations. The objectives were:

1. to assess the likely amount of nitrate leaching for three existing cropping systems in northern Italy; and
2. to quantify the reduction of nitrate leaching when fertilization rates were determined from expected crop uptake based on target yields rather than conventional application rates ('tactical' versus 'conventional' nitrogen application).

This study included two predominantly lowland areas situated in the provinces of Modena and Piacenza. Soil texture and organic matter data for each soil horizon were provided by Servizio Cartografico della Regione Emilia-Romagna. The hydrologic parameters necessary for the simulation were computed by the SOILPAR software (Donatelli et al., 1996). Daily meteorological data (precipitation, and

Table 1
Average simulated amount of nitrate leached in response to nitrogen management (conventional or tactical) for three crop rotations and two locations in Italy[a]

		Modena			Piacenza		
		Sb-W	M-M-W	M-Sy-W	Sb-W	M-M-W	M-Sy-W
N applied (kg ha^{-1} $year^{-1}$)	Conventional	180	260	177	180	260	177
	Tactical	115	160	117	115	160	117
N leached (% applied)	Conventional	0	30	11	6	35	19
	Tactical	0	13	0	3	20	5

[a] The crops are sugerbeet (Sb), wheat (W), maize (M) and soybean (Sy)

maximum/minimum temperature) characterizing each of the two areas for a 50-year period were generated using the ClimGen weather generator (Stöckle and Nelson, 1998). The daily solar radiation data were then estimated using the model proposed by Donatelli and Campbell (1998).

The study quantified the variability of leaching as a function of the amount of potentially leachable nitrogen in the cropping system (Table 1). In contrast to local expectations and general assumptions made by policymakers, simulation results suggested that leaching is not an inevitable consequence of cropping in these regions. Even in cases of elevated levels of nitrogen application and under unfavourable soil-climatic situations, nitrogen leaching does not necessarily follow (e.g. sugarbeet — wheat rotation; Table 1). Hence, current fertilizer recommendations might result in the loss of yield potential without further enhancing sustainability or reducing off-site effects of cropping. Further, the choice of rotation and the amount of nitrogen applied can have substantial impacts on nitrate leaching (Table 1).

The study demonstrates that a dynamic modelling approach has much to offer for policy-related decisions. It has the potential to greatly contribute to a more informed debate about agricultural production and systems management within the context of natural resource management. Asseng et al. (2001a, b), for instance, used a similar simulation approach to investigate options to reduce deep drainage (the major cause of dryland salinity) under wheat crops in Western Australia. Such analyses provide policymakers with objective means to gauge and compare the impact of policy options. At the same time, these tools allow producers to assess the effect and impact of compliance with legislation. The challenge remains to actually integrate such approaches into policy frameworks that result in improved farm incomes and increased environmental benefits for the greater community. Engaging policymakers and producers in the process of systems analysis might provide both groups with the necessary insight and data for a more informed and equitable debate that could positively influence future policies as well as management responses to these policies (Ten Berge et al., 1997).

4. Regions with high climatic variability, small areas, low input and subsistence agriculture

In such environments, food security is often of overwriting concern and productivity can only be increased if this is not associated with increased risk. Simulation modelling can be used to assess management impacts in terms of productivity gains and associated risks. However, the lack of credibility of the tool is generally the major stumbling block for adoption of novel management strategies. Lee (1993) tells the story of a Kenyan smallholder farmer who succeeded in transforming his farm from one that provided inadequate food supply for his family to one on which a food surplus is regularly produced. This transformation was achieved by judicious use of organic and inorganic fertilizers. Impetus for this beneficial change in farming practice was provided by a research project centred around the application of a simulation model demonstrating the production and risk consequences of alternative management practices such as fertilizer applications (McCown et al., 1992). This success on one farm has since extended to a further 106 farms in this district via a local self-help farmer group (Lee, 1993).

Clear evidence of how simulation may impact on farming practice in smallholder agriculture in Africa? A cautious maybe! The full story is that this farmer was a driver assigned to the research project. He was in the advantaged position of being able to closely observe project activities including on-farm trials with fertilizer and simulation analyses. Such close exposure convinced him that a FASE (Fertiliser-Augmented Soil Enrichment) strategy for combining applications of chemical fertilizer with manure and crop residues (McCown et al., 1992) provided a viable option for his own farm.

4.1. Farmer interactions

The work of McCown et al. (1992) suggested that the use of the simulation model permitted the assessment of fertilizer use in a way that would not have been possible using traditional field experimentation alone. Subsequent research has confirmed both the apparent attractiveness of fertilizer use in Africa and the applicability of models for addressing such research questions (Singh et al., 1993; Rötter and Van Keulen, 1997). Waddington (1993) agreed with the potential of models to increasing research efficiency and praised the research of McCown et al. (1992) as leading to greater understanding of the agronomic interactions, and in providing confidence to promote the use of N fertilizer on maize in semi-arid Africa. However, he also concluded that these benefits were not easily appreciated by farmers and few farmers had adopted N fertilizer as a management practice. This result is hardly surprising given Waddington's admission that there had not been widespread adoption of technology outputs from farming systems research by farmers generally.

In addressing the relevance of biophysical and economic systems modelling to developing countries, Lynam (1994) suggested that "the assumption that the modelling represents actual farmer decision making has become increasingly unrealistic, and the results are useful only for public policy formulation". This view seems to have prevailed amongst the research community faced with the dual intractable problems of generally poor adoption of technology by smallholder farmers, and the perceived enormity in jumping from normative simulation outputs to real farming. The reality is that most simulation analyses reported for Africa or elsewhere are normative analyses conceived and applied by researchers to determine optimal management or policy strategies for how farmers should behave in an idealized world. It is no wonder that Goldsworthy and Penning de Vries (1994) report the conclusion from a workshop addressing this issue that "the principal use of agricultural systems models is to explore what the probable outcome of different policies or planning strategies is likely to be" (p. 99).

Can this conclusion be challenged? Does the single example above of an African farmer being influenced by on-farm research and modelling (added to the other examples cited elsewhere in this paper) suggest a more direct engagement of African farmers, as opposed to invention solely via government policy, may have benefits?

McCown and Cox (1994) certainly believe that the participatory on-farm research and modelling approach employed with farmers in Australia is a reproducible and transferable research methodology that may be also applicable to Africa.

Are such tools relevant to smallholder farmers in the semi-arid tropics of Africa? In addressing this question, both ICRISAT (International Crops Research Institute for the Semi-Arid Tropics, India) and CIMMYT (Centro Internacional de Mejoramiento de Maiz y Trigo, Mexico) are currently collaborating with APSRU on two projects targeted at testing the relevance of the APSIM model to smallholder agriculture in the semi-arid tropics of India, Zimbabwe and Malawi. Both projects are aimed at using APSIM with farmers, NARS (National Agricultural System) professionals and NGOs (Non-Governmental Organization) in the evaluation of farm management options. Accordingly, a number of on-farm case studies are being implemented as part of these projects, whereby participatory on-farm research trials are negotiated and conducted with farmers on issues identified via simulation analyses relevant to the participating farmers' own livelihood strategies.

Whether the model has a role in direct intervention with smallholder farmers is viewed differently among the researchers involved in these projects and, consequently, this question forms the basis of a researchable issue in itself. The consensus view is that systems models such as APSIM, CropSyst or DSSAT may identify management options worth exploring in on-farm experimentation, with the expectation that the process of identification and development of new technologies may be expedited. Some consider that it is also possible to directly engage smallholder farmers with the model in 'What if?' analysis and discussions on issues of interest to them. Whether this is the case is being explored by APSRU using a Participatory Action Research methodology, where each researcher–farmer interaction involving APSIM follows an iterative cycle of planning the interaction, acting on the plans, observing and documenting what happens, and reflecting on the interaction's outcomes in order to repeat the process a next time.

4.2. Climate forecasting and modelling

The demand for secure and sustainable food production in developing countries continues to increase. The challenge is particularly great in rainfed production systems in the semi-arid tropics (SAT) of India and Africa, where Green Revolution technologies have had relatively little impact. Frequently, problems are related to the inability of farmers or policymakers to anticipate and make proactive adjustments to climate variability. Experiences in Australia, the USA and South America have shown that the emerging capacity to forecast future rainfall and temperature distributions, used in conjunction with cropping systems simulation, can substantially contribute to increased agricultural productivity and farmer livelihood, underpinned by more appropriate natural resource management (Meinke and Hochman, 2000). This has been recognized by international bodies such as the WMO (World Meteorological Organisation), who through the International START Secretariat (Global Change System for Analysis, Research and Training, co-sponsored by the Global Programs IGBP, IHDP and WCRP) have initiated the CLIMAG project.

CLIMAG (Climate Variability and Agriculture) aims to utilize the growing ability to predict forthcoming climate variations to improve cropping systems management and decision making and increase production at local, national and international scales.

One of these projects, financially supported by APN and START, uses locations in southern India and northern Pakistan as case studies to demonstrate the utility and feasibility of combining seasonal climate forecasting with a structured, agricultural systems research approach in developing countries. With the help of the international agricultural modelling community under the auspices of ICASA, the project provides a means to assess the potential value of seasonal climate forecasting to agricultural producers in these regions. The ICASA initiative draws together the worlds major groups involved in agricultural systems analysis and modelling. ICASA's board includes Wageningen University and Research Centre (WUR) and partners, many scientists from around the world (e.g. University of Florida, GISS-NASA and others) and APSRU from Australia. The project also provides links to the International Research Center for Climate Prediction (IRI, Columbia University New York) and partner institutions in India and Pakistan. It is expected that project outcomes will eventually provide an internationally recognized framework for effective delivery of seasonal climate forecasts in rainfed systems of the SAT. To achieve these aims requires clear identification of key decision points within this farming system in terms of their (1) technical possibility and (2) socio-economic feasibility.

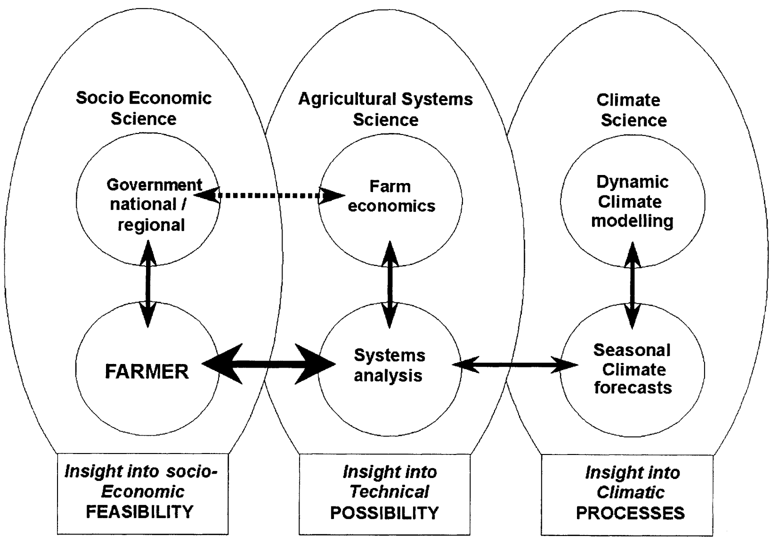

Fig. 1. Programme concept — disciplines, relationships and linkages for effective delivery of climate information for decision making. Operational links are indicated by the solid arrows. Dashed arrows indicate areas where an operational connection is still weak or does not exist and where the larger programme needs to develop components for true 'end-to-end' applications. Solid arrows indicate links that have proven useful in the more developed parts of the semi-arid tropics (i.e. Australia, USA and South America).

The project will deliver an agronomic and climatological systems analysis of cropping systems in parts of India and Pakistan including clear recommendations on where additional research efforts are needed according to the general framework presented in Fig. 1. This will include quantification of strategic management opportunities in these cropping systems and testing of existing analytical models. Interdisciplinarity and the human dimension are at the core of this approach whereby technically possible solutions will be evaluated in terms of their socio-economic feasibility.

The technical issues to be addressed are rather specific: agricultural production in the Indian state of Tamil Nadu experiences problems due to erratic monsoon seasons, crop failures and often inappropriate resource management. Average annual rainfall is 640 mm with most rainfall received during two monsoon seasons, namely the south-west monsoon (172 mm; June–September) and north-east monsoon (321 mm; October–December). For this part of India, the use of SOI phases (Stone et al., 1996) has shown some skill. There is a significant relationship between seasonal rainfall and negative phases of SOI, with a stronger signal during the north-east monsoon (Table 2). In both seasons, variability is less in negative SOI phases with the chances of getting at least median rainfall considerably higher than in other years.

The average dryland crop production in this region of Southern India is about 0.6 t ha^{-1}. The key management decisions are selection of crop, dates of sowing, land management, fertilizer rates, crop management and harvesting operations. Seasonal climate forecast could help to increase production by making better informed management decisions. For instance, preliminary simulation results indicated that if the median August–November rainfall probability is above 400 mm and the soil profile contains at least 50% of stored soil moisture by 15 August, it is advisable to plant cotton. If the condition is not satisfied it would be better to consider planting sorghum between 15 September and 15 October, provided the median September–December rainfall probability exceeds 300 mm and stored soil moisture is above 30%. Otherwise millets, sunflower and chickpea could be considered. Using APSIM we conducted a simple economic analysis on the simulated results.

The analysis showed that in 7 out of 9 years when the SOI was negative at the end of July, returns from the seasonal climate forecast-based system were higher than those for the non-responsive system. In two of the years simulated, returns were marginally lower than for the non-responsive management. The overall result was a

Table 2
Probability of exceeding the long-term median rainfall during either the south-west monsoon (SWM) or the north-east monsoon (NEM) in relation to the five SOI phases preceding these seasons

SOI Phase	SWM (%)	NEM (%)
Negative	80	75
Positive	55	47
Falling	42	46
Rising	35	30
Near Zero	30	58

significant, ca. 20% increase in financial returns and a reduction in yield variability or production risk. Although climate signals in India differ from those in Australia, the overall outcome of applying seasonal climate forecasts was similar to results reported by Carberry et al. (2000) for a grain/cotton system in Northern Australia.

This example shows how such a seasonal forecast combined with a sound modelling approach allows objective evaluation of alternative management options and quantification of associated production risks. While there is no doubt that the proposed management strategies are technically possible, the feasibility of these options still needs to be investigated. This requires an analysis of similar rigour to establish if within the existing socio-economic structures and production environment the proposed management adaptations are feasible and acceptable. As with the biophysical/economic systems analysis, entry points need to be identified that are likely to result in largest benefits to individual producers and the entire community.

5. Synthesis

A common thread throughout the five case studies is obvious: systems analysis and, more specifically, crop modelling has the potential to increase profitability and reduce the on- and off farm risks of agricultural production. Building sound, physiologically based models is an important and exciting activity for scientists and software engineers. Novel model applications challenge our thinking and our further understanding of the systems under investigation. However, these scientifically rewarding activities will remain without impact as long as they stay within the comfort zone of biophysical science. It is unsatisfactory to simply claim (as is frequently the case) that a desk top simulation analysis will have important implications for decision making. Often, researchers make statements about applications for decision making without a clue as to what is necessary to make it work. Pay-offs can only be expected when a truly integrated systems approach is employed that includes decision makers as partners and guarantees that they have ownership of this process. This truly participatory approach — as shown in the case of Australia and Uruguay — ensures that the issues that are addressed are relevant to the decision maker. This process will also ensure that there is sufficient scope for the decision maker to alter their behaviour/management based on the information provided. This 'ability to move' might be constrained by external factors such as current policy settings (as in the Italian example) or international market forces. A clear identification of these constraints can help to either collectively lobby for change (in case of the former) or to decide when taking action might be appropriate or profitable (in case of the latter).

In order to aid the decision-making process, a modelling approach must reduce complexity rather than proliferate choices. This requires precise and unambiguous problem definition and scenario analyses that quantify outcomes in terms of economic and environmental consequences. Again, this is most likely to be achieved through a true participatory approach that generates ownership of the process and confidence in the model's ability to simulate real farm outcomes (Carberry and

Bange, 1998). This process contextualizes model applications within the context of an individual decision maker's situation but depends strongly on a rather time consuming one-to-one interaction that, from a research perspective, is not sustainable. While some of this might be overcome in more developed economies through a 'fee-for-service' approach by involving agribusiness, careful consideration should also be given to more normative approaches (e.g. decision support software) that can reach a wider audience quickly. In spite of the poor track record of decision support products (Plant, 1997), they are still likely to have a role when properly integrated into group processes as outlined earlier (Hammer et al., 2001). We suggest that a tandem approach is necessary whereby participatory approach is essential in the early stages of model application for confidence building amongst client groups. As these relationships mature and clients become more confident and proficient in model applications simple decision tools will become increasingly useful and important. This is likely to be the case regardless of client group, be they farmers, extension staff, agribusiness or policymakers.

One of the biggest remaining challenges is the successful implementation of this integrated systems approach in developing countries. As the African example has shown, impact is often achieved more by chance than design. The Asian example, which focuses strongly on the use of models within the context of climate variability and seasonal climate forecasting, attempts to capitalize on the success in countries such as Australia and Uruguay. This is not a straight forward process because differences between these regions are not only biophysical, but (and probably more importantly) institutional, cultural and socio-economic. It will remain a considerable challenge to identify appropriate entry points for modelling related technology under such circumstances. Eventually, this might lead to better adoption of fully integrated systems approaches and result in the development of resilient farming systems that are in tune with current climatic conditions and adaptable to biophysical and socio-economic variability and change.

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