Europ. J. Agronomy 32 (2010) 51–58

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

How farming systems simulation can aid the development of more sustainable smallholder farming systems in southern Africa

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ARTICLE INFO

Article history:
Received 8 July 2008
Received in revised form 4 March 2009
Accepted 14 May 2009

Keywords:
Sub-Saharan Africa
Crop model
APSIM
Maize
Legume crop
Smallholder farmers

ABSTRACT

Over the past 20 years, farming systems modelling has become an accessible tool for developing intervention strategies targeted at smallholder farmers in southern Africa. Applying the Agricultural Productions Systems sIMulator (APSIM) to credibly simulate key soil and crop processes in highly constrained, low yielding maize/legume systems has led to four distinct modes of use: (i) to add value to field experimentation and demonstration; (ii) in direct engagement with farmers; (iii) to explore key system constraints and opportunities with researchers and extension agencies; and (iv) in the generation of information for policy makers, bankers and insurance institutions. Examples of application in each of these modes are presented. Despite being demonstrated as an excellent tool for developing intervention strategies and extension material, the use of simulation is limited by a lack of competent local users. Better co-operation within the simulation community, sharing of climate, soil and crop parameterisation and validation datasets, and focussing of efforts on using models to benefit smallholder farmers are suggested as ways of increasing the use and relevance of simulation. Substantial investment in the training of agriculturalists and the further science development of systems simulation is required to tackle the enormous challenges facing agricultural development in the region.

1. Introduction

Resource poor farmers are the focus of many research and development projects in the developing world. Poor adoption of technological innovations from many agricultural research projects has resulted in greater emphasis by donor agencies on achieving farmer adoption and adaptation of technologies. This has led many researchers to operate in a participatory research context by recognising that the biophysical ‘production system’ is made up of crops, pastures, animals, soil and climate together with inputs and outputs as well as the ‘management system’ made up of people, values, goals, knowledge, resources, monitoring opportunities and decision making (Keating and McCown, 2001).

In the semi-arid regions of southern Africa, smallholder farmers face serious challenges to maintaining food security exacerbated by low soil fertility, limited resources to purchase inputs and highly variable rainfall. In these environments, water and nutrient use efficiency are low (Mapfumo and Giller, 2001; Mushayi et al., 1998) and technical options for improving soil fertility and production are limited by a range of factors, which include the poor resource endowment of farmers and their aversion to risk (Tittonell et al., 2007a,b). Farmers attempt to manage this risk by utilising the spatial variability of their landscape and on-farm resources (Giller et al., 2006) and through the timing of operations such as planting and fertilising (Harrington and Grace, 1998). Simulation models have proved to be useful in capturing the interactions between climatic conditions, soil types and nutrient dynamics in cereal based farming systems in Africa and Australia (Carberry et al., 2002b). In Africa, the development of the Agricultural Productions Systems sIMulator (APSIM) (Keating et al., 2003) model has been pursued in collaboration with several Consultative Group for International Agricultural Research (CGIAR) institutions and their National Agricultural Research and Extension Service (NARES) partners since 1985 (Carberry, 2005).

Keating and McCown (2001) summarised the use of computer aided farming systems analysis and intervention that has evolved over the past 40 years. Many modelling efforts have continued because of the “potential” benefits for aiding agricultural developments, rather than the widespread use of models for assisting in making land management decisions. These authors criticised many modelling efforts (decision support systems, expert systems) for their lack of attention to a systems perspective, especially for not

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doi:10.1016/j.eja.2009.05.004

Table 1
Summary of studies reporting the application and performance of APSIM in smallholder farming systems in southern and eastern Africa.

Study	Location	Cropping systems, treatments
Carberry et al. (1996)	Kenya	Intercropping of legumes with maize
Chivenge et al. (2004)	Zimbabwe	Maize response to N supply from manures and inorganic fertiliser
Dimes and Revenuru (2004)	India	Sorghum and pigeonpea response to N and P inputs as manure
Dimes et al. (2003a)	India	Crop coefficients for P responses in sorghum, pigeonpea, and groundnut.
Keating et al. (1999, 2000)	Semi-arid Zimbabwe	Weed density and NUE in maize
Ncube et al. (2009)	Semi-arid Zimbabwe	Legume growth and yield and rotational effects on maize
Probert (2004)	Kenya	Response of maize to various fertiliser and rock P sources
Probert et al. (2004)	Kenya	Modelling farm yard manure in low input systems
Robertson et al. (2000)	Malawi	Maize response to low N inputs
Robertson et al. (2001)	India and Australia	Pigeon pea simulation model
Robertson et al. (2005)	Malawi	Maize in rotation with green manure (*M. pruriens*) and rates of N fertiliser
Shamudzarira et al. (1999)	Semi-Arid Zimbabwe	Rates of N fertiliser on maize
Shamudzarira and Robertson (2002)	Semi-Arid Zimbabwe	Monoculture maize, N fertiliser rates across seven seasons
Whitbread and Ayisi (2004)	South Africa	Maize with response to N
Whitbread et al. (2004c)	Zimbabwe	N × P interaction in maize

engaging the end user. Doyle (1990) found that "the failure of systems researchers to liaise with farm decision makers has meant that farmers [farmers that have been exposed to modelling] are rightly suspicious of computer generated predictions of optimal resource use."

According to Carberry et al. (2004) simulation modelling (in developed countries) has struggled for relevance in real-world agriculture and for impact on farmer decision-making. These authors criticise context free model applications where researcher-designed management scenarios are tested under hypothetical situations with recommended actions suggested on what managers should do, generally without any reference to real-world testing. There are few examples or citations where farming practices have benefited from such modelling studies. Matthews and Stephens (2002) reviewed the application of simulation models in developing countries and sought examples of where such models have been useful in smallholder farming systems. Unfortunately, this extensive review largely failed to identify any noteworthy examples of where crop simulation models had impacted on the practices of smallholder farmers. The 11 examples presented to demonstrate possible impact were mostly via influence on research direction, e.g. designing new rice plant types to increase yield potential or weed competitiveness (Dingkuhn et al., 1997), or in the training of local researchers, e.g. the SARP project (ten Berge, 1993).

In Australia, an example where the use of simulation can be relevant and significant to farmers in certain situations is found in the FARMSCAPE experience reported by Carberry et al. (2002a). FARMSCAPE (Farmers', Advisors', Researchers' Monitoring, Simulation, Communication and Performance Evaluation) is a program of participatory research with innovative Australian farmers and their advisors who work with researchers in the context of their own farming operations. There have been a number of documented examples of where model-based intervention with farmers has lead to on-ground change in management practices (Carberry et al., 2002a).

Inspired by the experience of using models with Australian farmers and cognisant of the circumstances that African farmers face in terms of seasonal risk, resource constraints and a range of management options, our group have been using simulation models for the last 20+ years in eastern and southern Africa in an attempt to achieve meaningful change in farmer practices. Models have been applied in a variety of modes with farmers and their associated change agents (such as extension agents, fertiliser sellers and rural banks). It is timely to review the experiences with such approaches and propose a way forward for model-based intervention in smallholder agriculture. Our experiences are mainly drawn from work conducted in Kenya, Malawi, South Africa and Zimbabwe between 1985 and 2008, primarily in maize-based farming systems.

2. Adapting crop modelling for smallholder farming systems

A first step in applying crop simulation models to smallholder circumstances in southern Africa has been to modify the models to account for a range of constraints that are typically not seen in broad-acre cropping environments in Australia. This issue was first recognised by Carberry and Abrecht (1991) and Keating et al. (1991). Cereal crops in smallholder agriculture are often much lower yielding than under the commercial situation. The crops grown by smallholders are usually at low plant density, inorganic fertiliser inputs are limited and available, farmyard manure may be applied. These crops are often compromised by significant weed competition and nutrient deficiencies, grown in a variety of configurations with other species such as legumes (Waddington et al., 1991). Several years of effort has been put into the necessary model modifications and a summary of published work is provided in Table 1. The modifications fall into three categories. The first of these is ensuring that the models are able to simulate the low yields (e.g. < 1 t/ha for maize) seen often in smallholder fields (Shamudzarira et al., 2000) in the semi-arid tropics by including effects of low yields induced by barrenness in maize, open-pollinated varieties that have lower yield potential than hybrids and the low plant densities often seen in farmer's field (e.g. 1.5–3 plants/m^2 in maize). The next category includes accounting for yield constraints such as weeds (Shamudzarira et al., 1999), which are a common yield-limiting occurrence in smallholder situations, and low phosphorus status of soils with low rates of applied fertiliser P (Probert, 2004). The use of farm yard manure often provides the only input of P into these systems (Probert et al., 1995). To address this issue it was necessary to develop models that could describe the release of N and P from such sources (Dimes and Revenuru, 2004; Probert et al., 2004, 2005), which is a significant source of P in smallholder systems. Finally, farming systems in southern Africa consists of not only conventional forms of maize monoculture but also intercropping (Carberry et al., 1996), relay cropping and green manuring (Robertson et al., 2005), legume crops such as pigeon pea (Robertson et al., 2001) and other cereals such as millet (van Oosterom et al., 2001). This required credible simulations for the diversity of legumes and associated management systems found in southern African farming systems (Ncube et al., 2009). The result of these modifications has been a credible cropping systems simulation capability that has been used in a range of applications.

3. Modes of use of crop models

Through actively using crop-soil simulation models in southern and eastern Africa for the 20+ years, we can discern four main modes in which these models are deployed. Each of these modes of use is presented in the following sections along with examples of their practical application.

3.1. Adding value to experimentation and demonstration

This encompasses the interpretation of experiments, assessing new technologies and incorporating seasonal variability and risk into the interpretation. A major benefit is being able to develop an understanding of treatment responses over a range of seasons (Ncube et al., 2007, 2009) and being able to develop extension guidelines. Models offer great promise in making efficient use of scarce research resources, by being able to extrapolate to a wide range of seasons, soil types and management regimes. However, the parameterisation and initialisation of models requires high quality data. In our experience, it is common for on-farm experiments to be unintentionally compromised by weeds, pests and nutrient deficiencies, and without measurements of these constraints it is impossible to account for the discrepancy between observed and simulated yields.

For the first mode of use, an example is drawn from "The Risk Management Project" that operated from 2000 to 2004 and focussed on experimentation with various legume/fertiliser practices to restore soil fertility in highly resource-constrained smallholder farmer systems in Malawi and Zimbabwe. The farming practices assessed included: the response of maize to low N-fertiliser application rates; the potential use of leguminous cash crops (soybean, cowpea) in the place of maize; green manure (mucuna, pigeon pea) legumes in rotation with maize. Each of these practices was tested with farmers in extensive on-farm experimental programs (Kamanga, 2002) and APSIM was used to simulate the field results and build an understanding of the key drivers of the system.

In a smallholder maize growing area close to Masvingo in Zimbabwe low application rates of fertilizer N to maize have been promoted to resource poor farmers by CIMMYT and ICRISAT (Dimes, 2002). Field trials over several seasons and simulation were used to investigate the consequences of applying N in a range of situations that occur in the field. It was shown that poor weed control caused low nitrogen use efficiencies (NUE) with the best NUE obtained at higher planting densities, on deeper soils and good weed control (Fig. 1a). This example also provided some insights as to why farmers persist with lower than recommended plant populations in the target district – experience has shown them that at their low levels of soil fertility, planting maize at low population was most often the most efficient and lowest risk strategy.

In a second example of this approach, *Mucuna pruriens* was evaluated as the most reliable green manure legume and its potential to improve maize growth in subsequent crops was investigated (Kamanga et al., 2003; Whitbread et al., 2004b). The simulation analysis showed that significant responses in maize growth to mucuna in the previous season, relative to a maize-on-maize control, occurred only when the mucuna crop was incorporated at flowering (Fig. 1b). In Zimbabwe, farmers found that this was an impractical system and were unlikely to adopt a system that required high labour input to capture the benefits. In the higher rainfall environment of Malawi, green manure systems were found to have a much higher reliability (Robertson et al., 2005).

3.2. Direct engagement with farmers

Following the Australian experience of directly engaging farmers with simulation models through the FARMSCAPE program (Carberry et al., 2002a) attempts have been made to replicate this with smallholder farmers in southern Africa. Examples of this approach are given by Carberry et al. (2004) and Whitbread et al. (2004a) based on a workshop convened at ICRISAT-Bulawayo in Zimbabwe in 2001 to explore the complementarities between farmer participatory research approaches and computer-based simulation modelling in addressing soil fertility management issues at the smallholder level (Twomlow, 2001). To test the complementarities of these two approaches, six teams were assembled made up of computer simulation modellers trained in the use of the cropping systems model APSIM, participatory researchers (agronomists, economists and social scientists) trained in participatory rural appraisal and rapid rural appraisal tools and methods, and local researchers knowledgeable on African farming systems. The six teams then worked with farmers in six villages in the Tsholotsho and Zimuto districts, Zimbabwe, for 3 days. They used participatory tools to build realistic farm scenarios for the computer simulations, which were then run for the farmers to get their reactions and suggestions for improvements.

Carberry et al., 2004 reported that "...it was a surprise that computer simulation was apparently relevant to smallholder farmers in Zimbabwe." Relevant evidence included: the ready participation of farmers in specifying questions for simulation; in volunteering likely outcomes; in rationalising their expectations with simulated outputs; and in re-specifying the question for the next simulation run. The farmers in this engagement were not passive participants; rather they acted as experts in their own domain, using the simulator to explore possible consequences of altered management. Following on from this interaction between researchers and farmers at Tsholotsho, three more seasons of on-farm experimentation

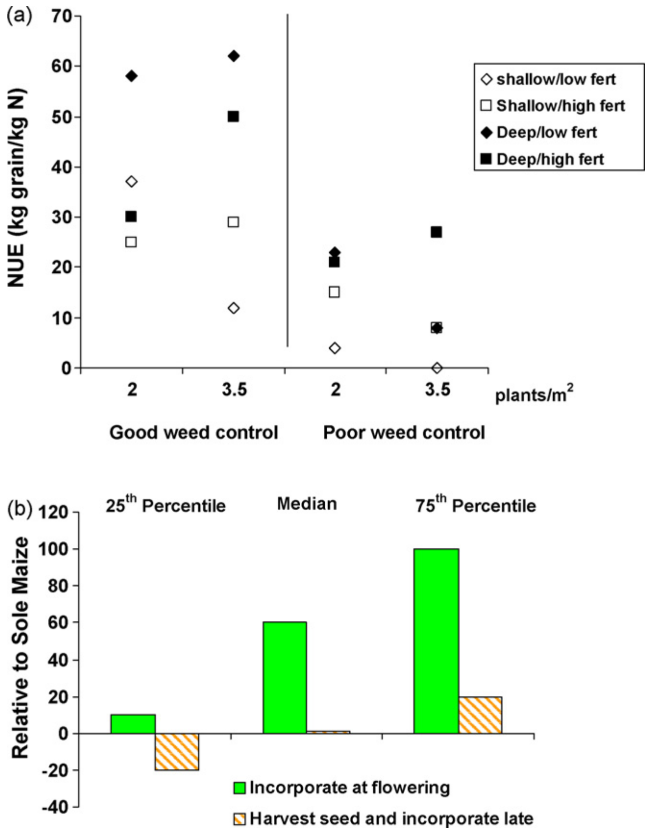

Fig. 1. (a) Simulated nitrogen use efficiency (NUE) of fertilizer N applied at a rate of 15 kg/ha at sowing for simulated scenarios of two densities of maize grown in shallow (0.5 m) or deep (1.7 m) soils of high (organic C 1.4% topsoil) and low fertility (organic C 0.4% topsoil) and poor (100 days after sowing) and good (100 days after sowing) weed control. (b) The simulated yield response of dryland maize grown following a mucuna green manure crop that is incorporated at flowering or after seed set. The percentile responses were derived from simulations using historical weather data (1950–2005).

were conducted with about 35 farmers and have demonstrated large maize yield gains from low doses of fertiliser (as little as 10 kg N/ha) (Ncube et al., 2006).

Whitbread et al. (2004a) reported from their experiences that "During a series of facilitated discussions, the Zimuto farmers identified labour and resources constraints as key constraints to soil fertility management and enhancement of maize yields." Scenario development using APSIM contrasted maize growth with the application of inorganic fertiliser or manure resources. The choice between expending effort to collect poor quality manures, or the use of this labour to obtain small amounts of fertilizer could be weighed up in terms of potential maize yields.

This approach has been repeated by the same authors on several more occasions in Limpopo Province South Africa to engage semi-commercial smallholder farmers in designing cropping systems that are more resilient under highly variable rainfall environments (Dimes and Whitbread in unpublished reports). These interactions also led to the initiation of on-farm experiments and changes in farmer practice, at least in the short term. This direct mode of engaging farmers with models requires an understanding of local crop management practices as well as daily climate data and soil characterisation – all essential ingredients to a successful interaction in the Australian context as well (Carberry et al., 2002a).

3.3. Exploring systems constraints and opportunities with researchers and change agents

In most smallholder situations where resources are highly constrained, the household or farm scale decisions about the allocation of labour, land and inputs are critical in efficiently deploying these resources. One approach is to build farm scale models that are able to consider these resources and their impacts on productivity to determine optimal management systems that maximise efficiency. The NUANCES approach (http://www.africanuances.nl; Giller et al., 2006; Tittonell et al., 2007a) has attempted this by using relatively simple point scale models and utilising the outputs, or production functions, in a farm scale bio-economic model. This approach has proved to be useful for exploring nutrient management strategies across soil fertility gradients (Chikowo et al., 2008; Rufino et al., 2007; Tittonell et al., 2007b). However, realistically representing the complexities of farms with models requires substantial investment in model development and extensive baseline data collection about the farm system (Herrero et al., 2007). A similar approach was also undertaken by McDonald et al. (2004) and MacLeod et al. (2007) with smallholder farmers in eastern Indonesia. In this example, APSIM was used to estimate the growth of major crop and forage crops, a monthly timestep animal production model to predict the growth and herd dynamics of the Bali *Bos indicus* component and a household socio-economic model was used to identify the economic returns and resource constraints associated with new forage-livestock opportunities.

An alternative approach that attempts to capture the key interactions and constraints that determine productivity within a farm system can be used to develop insights into farm scale resource allocation issues and from that develop practical extension advice. Dimes et al. (2002, 2003b) and Keating et al. (1999, 2000) report on such an approach where the discussion amongst researchers and farmers identified key constraints such as labour, the timing of weeding, and limited fertiliser applications. APSIM was used to develop an understanding of the key drivers of a maize crop and how it most efficiently responded to fertiliser N. Various model runs showed that efficient fertiliser response in the maize crop depended on weeding at the time of N application. Other insights into the management of scarce resources include spreading vs concentrating strategies for fertiliser or manure, opportunity costs and risks of occupying land for green manuring and comparing water and N use in legume or maize based systems. Whilst farm scale models do have a role to play in developing farm scale resource allocation strategies, more direct approaches focussing on farmer engagement and understanding and the development of extension material can arguably have a more immediate impact.

3.4. In the generation of information or systems understanding for policy makers, banking and insurance institutions, service providers

In the last 5 years, simulation modelling has also found a role in helping to inform policy makers, aid organisations, input suppliers and the banking and insurance sectors in making decisions that affect smallholder and emerging farmers. Two examples of this approach which have had notable impacts are reported.

3.4.1. Informing aid organisations and input suppliers

Few farmers in semi-arid areas of Africa use fertiliser and virtually none use recommended rates of application (Dimes et al., 2005). Essentially, the formal fertiliser recommendations of national research and extension systems have been ignored by smallholder farmers in Africa's extensive semi-arid regions. Because of this, productivity gains from fertiliser use remain grossly under-exploited. Over 160,000 smallholder farmers in Zimbabwe achieved 30–50% yield increases in their maize crops due to the aid-sponsored distribution of seed and fertiliser in the 2003–04 season (Carberry, 2005; Rohrbach et al., 2005). Most of these farmers were in the drier regions of Zimbabwe, where previous R,D&E efforts by ICRISAT and the local extension agencies had not included fertiliser. This initiative resulted in a short-term economic benefit for this large group of smallholder farmers in that particular season. This effort was to continue in the 2004–2005 season but was hampered by Government intervention. It is reasonable to predict a proportion of participating farmers would realise the benefits of applied N fertiliser and adopt this practice without subsidy. If so, the result would lead to economic, social and environmental benefits within these communities. Unfortunately this proposition could not be tested due to the political circumstances in Zimbabwe over the past 5 years. Key architects of the 2003 aid program readily attribute systems modelling within ICRISAT as being one source which supported the proposition of small doses of inorganic fertiliser applied in the lower potential regions of Zimbabwe (Carberry, 2005; Dimes and Twomlow, 2007). Consequently, modelling has become a core component within several follow-on projects within ICRISAT. Continued work on low fertiliser rates and engagement with agribusiness companies in southern Africa (Zimbabwe, RSA, Malawi, Mozambique) forms the basis of such effort. Already there are indicators of continued and widespread impacts with several agribusiness companies demonstrating interest in supporting fertiliser use by smallholder farmers

3.4.2. Support for the emerging farmer sector in South Africa

In South Africa, the post-apartheid land reform policies of land restitution and redistribution has created opportunities for the previously disadvantaged black African population to own and farm land. These new farmers, joined by farmers from the subsistence sector who are attempting to commercialise, now make up a third middle sector and are considered to be 'emerging farmers'. This trend represents an exciting opportunity that is enabling the black population to be part of the formal agricultural economy and to share in financial, social and environment benefits that this would enable (MacLeod et al., 2008).

The financial and insurance industries have begun to support the emerging farmer sector by providing credit and insurance services. Consequently, ICRISAT and the Banking Association South

Africa sponsored a workshop in September 2007 to explore the application of systems simulation in addressing climate risk for credit schemes which target emerging smallholder agriculture in drought-prone regions of South Africa. The two South African banks involved in the workshop had invested into emerging farmers in the 2006/2007 season with poor outcomes and so they were motivated to explore ways of increasing the success of future investments. Likewise, insurance companies underwrite such loans and so involvement of a representative of the SA Insurance Association was regarded as important to the workshop. Small group simulation scenarios were used to demonstrate how APSIM can be applied in exploring risk to financing cropping loans. Simulation of alternative management scenarios and display of Probability of Exceedence graphs were seen as exactly the information of benefit to banks and insurance companies. In addition, APSIM performed in line with expert opinion, and real credibility was gained and voiced during the course of the workshop.

Identifying low risk crop management strategies as well as setting the level of surety on which financiers can expect reward were the key attributes of interest gained from modelling. These results motivated the collective workshop group to request follow-up to explore how modelling can be better utilised in their current business systems–the most recent consequence was a meeting with one of the commercial banks in April 2008 to explore access to model applications to support their emerging farmer loan book. A real outcome of this activity was the confirmation of the agribusiness sector as key change agents within smallholder agricultural systems with whom systems researchers must partner.

4. Prospects for the future

In the harsh and unpredictable semi-arid environments common to many rainfed agricultural systems in Australia, crop and soil models, particularly APSIM, have become mainstream tools for developing strategies to manage soil fertility and crop production. Ensuring that models can play a greater role in developing effective interventions and practice change in the agricultural systems of southern Africa will require several of the following challenges to be considered:

4.1. Development of human capacity

Simulation modelling is a demanding exercise requiring training in computer use, data manipulation and interpretation and skills in systems agronomy. Whilst training has been a high priority of many research projects, building a critical mass of model aware scientists in Africa, has largely failed. For example, our experience in training 30+ professionals in the use of the models over the last 15 years has produced less than five scientists who could be identified as using simulation in their work (Carberry, 2005). Such lack of traction in training local NARES researchers in systems modelling mirrors the experience of others, most prominently, the Simulation and Systems Analysis for Rice Production (SARP) project funded by the Dutch government, which provided modelling training for rice-based farming systems in Asia (ten Berge, 1993). Further advances in human capacity to use simulation models will depend critically upon their incorporation into the syllabus of agricultural science training (Twomlow et al., 2008). Up until recently, model software was difficult to use and tended to frustrate new users, no doubt discouraging many from persisting. The APSIM software is now well engineered and able to be used by computer and database literate university staff and students with limited training. Making relevant weather, soil and management parameterisation available through the software releases and publically assessable databases would also increase the accessibility of this model.

The increasing trend for farmer participatory research and use of approaches such as mother-baby trials (Snapp, 1999) provides an opportunity for models to add value to such efforts through environmental characterisation, extrapolation and benchmarking of crop performance, similar to the way in which simulation models are being used in Australian efforts at on-farm research (Carberry et al., 2002a). With a need for greater efficiency in the use of research resources, models can provide a useful role in data-sparse environments, where limited replication and multiple constraints often confound the interpretation of treatment effects.

4.2. Sharing of resources and information between modelling groups

To date there has been more of a spirit of competition than cooperation between modelling groups and their respective modelling platforms. Most systems models require similar parameterisation (daily climate records, soil characterisation, and management logic) and information to validate model performance. In the case of soil characterisation, information critical to adequate model performance, the collation of soil survey information, generic soil profiles for regionally important soil groups, and techniques to derive critical parameters from existing datasets, as demonstrated by Hochman et al. (2001), are activities that underpin a whole range of RD&E activities in addition to systems modelling. As suggested previously by Struif Bontkes and Wopereis (2003) and Matthews and Stephens (2002), it would therefore be logical to develop information sharing arrangements. Until there are incentives such as joint projects, increased demand for modelled information and leadership through the CGIAR system and/or funding bodies, this prospect remains unlikely.

4.3. A greater awareness of the farm scale resource issues

A heightened awareness of resource constraints faced by smallholder farmers in terms of land, labour, fertility inputs (fertiliser and manure) has prompted recent efforts to build biophysically-based simulation models of households (e.g. Tittonell et al., 2007a). Such models are highly specific to household configuration and are demanding of input parameters in research environments that are typically data-sparse. Resources supporting the development of such modelling approaches that attempt to dynamically simulate whole farm systems could arguably be better targeted. We argue that simulating realistically the key components of any farm system needs sophisticated model capacity that can represent, for example, the subtleties of crop variety, planting time, residue management, the potential effects of elevated temperatures on phenology. All of these examples can profoundly influence farming system design and productivity and simple modelling approaches are unable represent such key drivers. Whilst model parameterisation to effectively represent the key land units/soil types on the farm is complicated by spatial variability, particularly in smallholder agriculture where soil fertility gradients exist (Tittonell et al., 2005), it is necessary.

An alternative to both of these approaches could be too combine the best elements of each by (i) using the sophisticated modelling capacity that is available through such platforms as APSIM and DSSAT to realistically represent the key drivers of the faming system (Chikowo et al., 2008) and (ii) use the household survey approaches to enhance the understanding of resource constraints and flows (Herrero et al., 2007; Tittonell et al., 2007a)

4.4. Incorporation of risk into extension material

In most smallholder systems, relatively simple agronomic improvements, able to be promoted by traditional extension methods, can result in large productivity increases. However, in general, simple and relevant recommendations are not being promoted by local government agricultural services. Much extension material produced from researchers and targeted at smallholder farmers in the past have been inappropriate. For example, optimum fertiliser rates, determined from dose-response experiments on research stations did not consider the fact that few smallholders could afford the high rates being recommended. Similarly, consideration of riskiness of the promoted technology is rare in extension material. Extension material produced by CIMMYT (2004) for Malawi and Zimbabwe, incorporated seasonal variation and risk into the suite of targeted recommendations by providing yield response to various management scenarios for each targeted region. A priority should be the development of extension material that is relevant for smallholders and the resource constraints that they face (Dimes, 2007). The decline of the public extension sector and the rise of NGOs in agricultural development in Africa, suggests that extension material should be developed and tailored with NGO input.

4.5. *Recognition of where models may contribute and their limitations*

Plant available N, P and water limitation are often the key constraints to crop productivity in many low input semi-arid farming systems. However, there are many other biotic and non-biotic factors that are not captured by simulation. Examples of these may include some effects of micronutrients, weeds, diseases, pest infestations, non-nodulation in legumes, water logging effects, plant population dynamics, soil structural constraints or rotational 'break-crop' effects. Some of these factors may be built into model output, for example increasing time to emergence or lowering plant population in the case of surface soil constraints. The effect of climate change on atmospheric CO_2 concentrations, temperature and rainfall increasingly needs to be considered where developing risk management profiles based on historical weather records.

Whilst acknowledging that all system constraints are unlikely to be fully captured in any simulation model, we argue that much can be achieved if the model does address the primary drivers of system performance – N, P and water limitations being of greatest relevance to much smallholder cropping in southern Africa. Combining realistic system modelling with knowledgeable understanding of the agronomic realities in each specific case can often compensate for lack of full comprehensiveness in system representation. However, the limitations of any modelling analysis need to be understood.

5. Conclusions

Over the past 20 years, farming systems modelling has become an essential tool for developing intervention strategies to benefit smallholder farmers in southern Africa. The development of APSIM to credibly simulate key soil and crop processes in highly resource constrained and low yielding maize/legume systems has enabled simulation to: add value to field experimentation; facilitate direct engagement with farmers to develop better understanding of key drivers of crop growth; explore constraints and opportunities with researchers and change agents; and generate understanding of key system drivers and seasonal variation for institutions and service providers. Whilst better co-operation within the simulation community could increase the use and relevance of farming systems simulation to the African context, substantial investment in the training of agriculturalists and the further science development of simulation is urgently required to build a critical mass of scientists that can tackle the enormous system challenges facing agricultural development in the region.

Acknowledgements

The Australian Centre of International Agricultural Research (ACIAR) funds project LPS/2002/081 in Limpopo Province on the Development of Emerging Farmer Crop and Livestock Systems.

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