

CROP GROWTH MODELS FOR DECISION SUPPORT IN THE SOUTH AFRICAN SUGARCANE INDUSTRY

VAN DEN BERG M and SMITH M T

*South African Sugarcane Research Institute, P/Bag X02, Mount Edgecombe, 4300, South Africa
maurits.vandenberg@sugar.org.za, marc.smith@sugar.org.za*

Abstract

The objectives of this paper are to present progress in crop growth modelling for decision support in the South African sugarcane industry, and to discuss possible directions towards better exploitation of the tools developed at SASRI. It is shown that their dynamic nature and process orientation make simulation models particularly useful as a basis for decision support systems (DSS) in crop management as well as for strategic decision-making. An overview of models and applications developed at SASRI is presented, and possible issues for future developments are discussed. These include possible refinements (e.g. regarding cane quality) and the inclusion of additional management practices (and their economics), such as fertilisation, trashing and ripeners. First and foremost it is necessary to assess actual DSS use and investigate the factors that inhibit (or enhance) adoption. To develop DSS tools that comply with the needs of the industry, potential beneficiaries must be involved from an early stage. This would also improve the synergies between research, model development and decision support.

Keywords: modelling, crop growth, decision support, sugarcane, technology acceptance

Introduction

Human beings do not take any conscious decision without consulting a model to assess the consequences of alternative options. These decisions range from 'whether or not to take an umbrella to go to work' to 'closing (or not closing) a contract to deliver a certain quantity of sugar at some moment in the future'. The models consulted are mostly conceptual models that exist in our minds. They are based on a combination of formal knowledge, empirical evidence accumulated over the years (called experience) and an intricate blend of other factors called 'intuition' or 'gut feeling'. Such mental models are very good at dealing with unstructured information and complex interactions between physical, social, psychological and economic phenomena. Moreover, they tend to be user-friendly, rapid and cheap. Mental models do, however, have weaknesses:

- Their ease of use and speed tend to decrease tremendously when they involve arithmetic operations, particularly when dealing with large sets of numbers.
- They are difficult to explain or transfer to others.
- Emotive aspects may contaminate rational aspects, affecting a correct assessment of the consequences of alternative decisions.
- Their great versatility and adaptability make it difficult to make an objective assessment of their accuracy.

These weaknesses are of extreme importance in agricultural decision support. They are addressed by additional tools such as decision trees, information sheets, nomograms or look-up tables, such as those that form the basis of the South African Sugarcane Research Institute

(SASRI) fertiliser advisory services (FAS). These tools have proven to be of great practical value over the past 80 years or more. However, they also become limiting when many calculations are needed, for example when keeping track of day-to-day changes in soil water content for irrigation management. Computers then seem to be the ideal solution because: (i) they can quickly and accurately perform complex calculations on huge sets of numbers and (ii) the program code to effect the calculations is well established, which facilitates testing and transfer to different conditions and by different persons. On the other hand, computer programs are expensive to develop and lack the versatility and adaptability of the human mind.

The above illustrates the complementarity of computers and the human mind with regard to their utility for decision support: The strengths of one offsets the weaknesses of the other, and *vice versa*.

The objectives of this paper are to present the state of crop growth modelling and discuss the way forward for decision support in the South African sugarcane industry. It is explained and illustrated why crop growth models are particularly useful as a basis for decision support systems (DSS¹) in crop management as well as for strategic decision-making and exploratory studies. An overview is given of models and applications developed at SASRI, and issues for possible future developments are discussed. Particular attention is given to the challenge to enhance the adoption and use of DSS tools by the industry, as discussed against the background of published experience and theory elsewhere.

Characteristics of crop growth simulation models

Introduction

Crop growth modelling began in the 1960s with the aim of increasing insight into crop growth processes by a synthesis of knowledge expressed in mathematical equations (Bouman *et al.*, 1996). The first decades following its inception were marked by ever-expanding models of increasing complexity, and optimism about the imminent replacement of costly field trials with cheap computer studies (Sinclair and Seligman, 1996). This was followed by a period of introspection during the 1990s, and it became clear that simulation modelling should be seen as a complementary tool for - rather than a cheap alternative to - classical research. In research, model development has now reached a more mature phase, where it is generally acknowledged as an invaluable aid to understanding the dynamic interactions between crop growth and the environment, linking different disciplines, helping to expose gaps in our knowledge, and exploring new fields of research that could never be addressed by field experimentation alone (Goudriaan, 1996; Boote *et al.*, 2001; Hammer *et al.*, 2002).

Basic principles

The spatial unit or 'system' described in most crop growth models is a crop plus the rootable soil below that crop. Some models operate at a farm, watershed or higher level, but calculations are usually done for points that are considered representative for individual fields, homogeneous soil units or grid-cells in a geographic information system (GIS).

¹ SASRI commonly uses the term Decision Support Program (DSP), whereas the term Decision Support System predominates in the international scientific literature. To avoid confusion, the term DSS is used throughout this text.

A schematic representation of a simple crop growth model is given in Figure 1. The method of describing the system dynamics is based on the so-called 'state variable approach'. As explained by Leffelaar (1993), this approach distinguishes three kinds of variables: (i) *state variables*, indicating quantities, such as leaf biomass per unit area; (ii) *driving variables*, referring to external factors such as solar radiation; and (iii) *rate variables*, indicating flows or rates of change.

Rate variables are determined by the state and driving variables according to our biophysical understanding. For example, the photosynthesis rate can be calculated at every time t on the basis of leaf area, water availability, temperature and solar radiation. Once all rate variables are calculated, the state variables are updated for time $t + \Delta t$; e.g. for the biomass of living leaves, L :

$$L_{t+\Delta t} = L_t + (G_t - S_t) * \Delta t$$

where G_t is the leaf growth rate, and S_t is the rate of leaf senescence at t . This procedure is repeated using the new values of the state variables as a starting point, and so on. It is important that the time interval Δt is sufficiently small to capture the dynamics of the rate variables. Most crop growth models use a time interval of one day.

The number of state variables that can be distinguished in cropping systems is discouragingly large. Not only the mass of the leaves is important, but also their surface area, position and biochemical composition. Weeds, soil animals and micro-organisms could also be included. It is possible to continue in this way *ad infinitum*. Therefore, attempts at constructing models on the basis of a full knowledge of all the biological, physical and chemical processes are completely unrealistic. Most crop growth models, including the sugarcane model CANEGRO (Singels and Bezuidenhout, 2002) keep track of some 50 to 100 state variables on the basis of approximately 10 driving variables, including daily weather data and management data such as irrigation and dates of planting and harvesting.

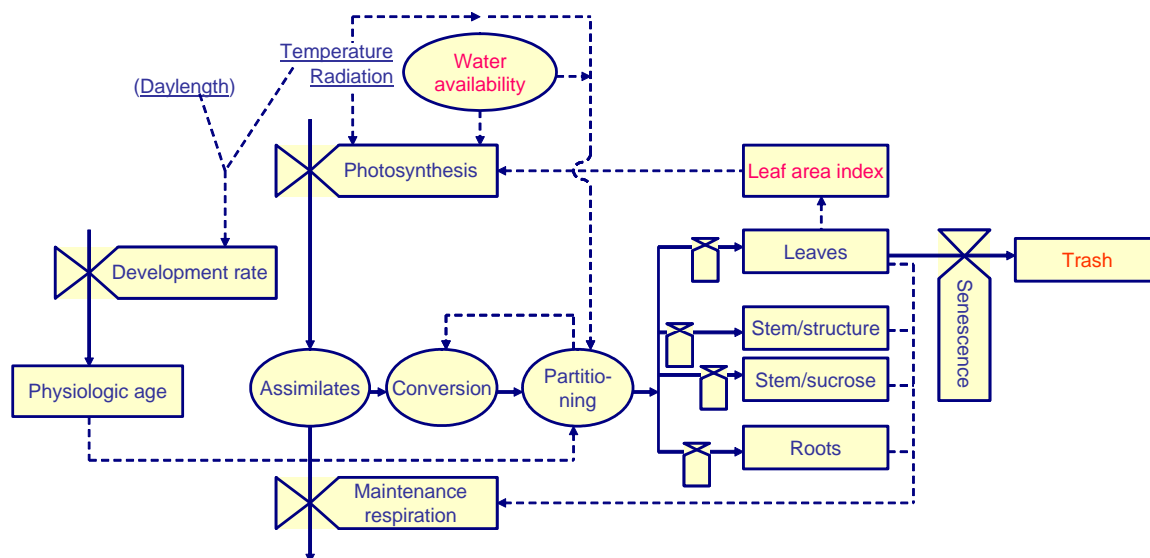


Figure 1. Relational diagram for the calculation of biomass accumulation in a simple sugarcane model. State variables are indicated by rectangles; rate variables by valves (⌘); driving variables are underlined. Ellipses indicate so-called intermediate functions. Solid arrows: fluxes (mostly of material); traced arrows: influences. Variables in red are part of the interface with a water balance module. Adapted from Bouman *et al.* (1996) and van Laar and Goudriaan (1997).

During their life cycle, crops are influenced by varying conditions affecting growth in varying ways. For example, a dry spell during canopy closure has a totally different effect on yield than a dry spell during ripening. Crop growth models that use calculations with daily time intervals have the potential to account for subtle changes even before they can be noticed visually.

The role of crop growth models in agricultural decision support

It is clear from the previous sections that, where the dynamics in crop growth have to be accounted for, nomograms, information sheets and mental models fall short in supporting agricultural decision making. Static yield models (e.g. Brüggemann *et al.*, 2001) are of no relevance to crop growth analysis and they lack the cause-effect mechanisms through which simulation models offer the possibility of assessing the consequences of alternative management.

These perceptions have resulted in an overwhelming number of applications as reported by Ten Berge and Stein (1997), Tsuji *et al.* (1998), Kropff *et al.* (2001), Ahuja *et al.* (2002), Matthews *et al.* (2002) and van Ittersum and Donatelli, (2003). An overview of applications for sugarcane internationally, is given by Inman-Bamber *et al.* (2001).

The role of crop growth models in decision support varies in accordance with the scope of the decisions concerned. The following paragraphs distinguish operational/tactical, strategic and exploratory scopes of decision making.

Support to operational and tactical decision making

The term ‘operational’ refers to decisions that are taken on a day-to-day basis (Stephens and Middleton, 2002a). Tactical decisions are typically taken at the beginning of a year or growing season. Crop growth models to support such decisions have been developed and applied, e.g. to optimise the timing of planting and harvesting (Bezuidenhout *et al.*, 2002), for irrigation scheduling (Bristow and Keating, 2003; Singels *et al.*, 1998), and to support nutrient management (Keating *et al.*, 1997).

Model output can be prescriptive, indicating, for example, when to irrigate and how much. More commonly, however, output is provided as conditional; for example, what yield can be expected if certain decisions are taken (e.g. to apply x mm of irrigation water next week instead of today). Such ‘what-if?’ models give the user the freedom to analyse trade-offs between the biophysical aspects and other dimensions of decision making which are better accounted for by mental models.

Another type of tactical decision support is crop forecasting (Everingham *et al.*, 2002), i.e. the prediction of climate and related yields over the current season or year. Crop forecasting can be of equal interest to growers, processors and the trading and marketing sectors, as well as to government bodies dealing with trade regulations or food security (van Diepen and van der Wal, 1995).

Support to strategic decision making

Strategic decision making typically refers to assessments of the impact of major changes in land management or substantial investments (Stephens and Middleton, 2002b). Examples are the introduction of new crops, trash blanketing versus burning (van Antwerpen *et al.*, 2002), alternative nutrient management strategies (Thorburn *et al.*, 2004), land purchase, and investments in irrigation (Singels *et al.*, 1999b; Lisson *et al.*, 2000).

More indirect forms of support to strategic decision making include environmental impact studies regarding nitrate leaching (Keating et al., 1997), yield benchmarking (Singels *et al.*, 1999a; Inman-Bamber *et al.*, 2001) and the calculation of attainable yields in land evaluation studies (Rossiter DG (2003). Biophysical models in land evaluation. In: WH Verheye (Ed). *Land Use and Land Cover*. Encyclopedia of life support systems (EOLSS). Developed under the auspices of UNESCO. Oxford, EOLSS Publishers, Oxford, UK (www.eolss.net: Topic 1.5.27). Yield benchmarking uses calculated attainable yields as a reference against actual yields. The difference between the two is called the yield gap (Matthews, 2002). At the farm level, fields with consistently large yield gaps require closer inspection for improved management. At a ward level, yield gap analysis provides insights to distinguish well-managed from poorly managed farms and, at the country level, governments may address regions with a large yield gap but high attainable yields as those where investments in agricultural development may be the most rewarding (IAC (2004). *Realizing the promise and potential of African agriculture*. Amsterdam, InterAcademy Council (available on www.interacademycouncil.net).

Exploratory use to support policy making

The exploratory use of crop growth modelling for decision support to governments or other entities, to develop more targeted innovation or adaptation policies, is mainly related to long term assessments. These include the possibilities of feeding the world population (e.g. Buringh *et al.* 1975), and the effects of climate change on crop production (Cheero-Nayamuth *et al.*, 2000; Cheero-Nayamuth and Nayamuth, 2001). Today, exploratory studies often elaborate on scenarios of different possible socio-economic futures in which, for example, climate change would have different consequences (e.g. Parry *et al.*, 2004). Such studies are usually conducted by interdisciplinary teams, using economic, environmental and other models in addition to crop growth models.

Limitations and pitfalls

Users of models should be aware of the limitations imposed by the quality of input data and the degree to which relevant processes are accounted for. On-farm comparisons between model results and actual yield records make sense only when reliable information on planting and harvesting dates and location-specific weather and soil data are available. Factors that are not accounted for in the model, such as pests, hailstorms and harvest losses should also be recorded. Simulated yields also contain inaccuracies as a consequence of the simplified process descriptions. Therefore, separating the effects of simulation errors from 'true' yield gaps requires statistical knowledge and at least basic understanding of the functioning of the model. Disappointing results can be expected when a model is applied outside the area of its original development without proper testing (van den Berg, 2000; Cheeroo-Nayamuth and Nayamuth, 2000). Such limitations are expected to decrease in time but will never completely disappear (Goudriaan, 1996). In this respect, results from crop growth models are not different from weather forecasts and macro-economic projections.

Crop growth models and applications developed at SASRI

CANEGRO (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002)

The CANEGRO model is the detailed research model of SASRI, which can only be operated by specialists. It is a daily time step, point-based simulation model, primarily driven by canopy development and radiation interception for photosynthesis. Biomass is dynamically

distributed between different plant components - including stalk sucrose - based on crop age, water stress and temperature. Water movement (e.g. runoff, gravitational flow and root water uptake) is simulated in a multi-layered soil profile. Practical CANEGRO applications include:

- the establishment of yield potentials for irrigated and rainfed conditions in South Africa to assist in the planning and development of new sugar production projects (Inman-Bamber, 1995);
- the calculation of yield responses to irrigation, used by engineers of the Department of Water Affairs to upgrade the canal system of the Pongola scheme (Inman-Bamber *et al.*, 2001);
- support to growers and millers in debates about the length of the milling season, by calculating the implications of an extended milling season for cane and sucrose yields (Inman-Bamber *et al.*, 2001);
- evaluation of harvesting strategies for irrigated crops at Tala Valley in the Midlands and for rainfed crops at Tongaat on the north coast (Bezuidenhout *et al.*, 2002).

Canesim

The Canesim model is a daily time step, point-based simulation model predominantly driven by water. For input, it requires the soil available water holding capacity and daily temperature, rainfall and reference evaporative demand as calculated by McGlinchey and Inman-Bamber (1996). The model accounts for partial canopy conditions and soil water content using a single layer soil profile. Yield is calculated as a function of transpiration. The water balance of Canesim is described by Singels *et al.* (1998), the canopy development by Singels and Donaldson (2000) and the yield calculation by Singels *et al.* (1999b). These publications also report on the validation of various aspects of the model against observed data. Canesim is the core model of the DSSs described below.

Crop forecasting (Bezuidenhout and Singels, 2001, 2003; Bezuidenhout, 2004)

The sugarcane yield forecasting system has been operational in South Africa since 2001. At the beginning of a year, mill operators use the forecasts to determine the opening and closure of the milling season, in order to maximise the quality of the cane crushed while staying within the mills operational capacity. Another tactical application of the model is to support decisions regarding future contracts for sugar sales on the world market. The calculations are performed for 48 homogeneous climate zones. Irrigation is simulated according to typical regional strategies, including water restrictions. The crop growth simulations use current weather data plus data from 10 historic seasons to substitute the (future) remainder of the season. The selection of these seasons is based on the climate outlook of the SA Weather Service. Country-level results (\pm monthly updates) are sent to 83 subscribers by e-mail. Results are also accessible through the internet, where different types of subscribers have access to different levels of information (countrywide, per mill or per homogeneous climate zone). For the March and April 2005 forecasts, 43 logins were registered from 13 different users.

*Internet yield benchmarking (Singels *et al.*, 1999a)*

This was the first internet based Canesim DSS, and was intended for use by growers to benchmark their yields and to roughly schedule their irrigation applications. The DSS has a minimal choice of inputs, namely (i) soil available water holding capacity (mm over the rooting zone), (ii) a weather station that is updated daily and (iii) an irrigation strategy. No

systematic user data are available, but feedback suggests that the DSS is quite popular. It has been used by millers, growers, Extension Officers and scientists (de Lange and Singels, 2003). The main criticism has been the inability to save scenarios, and the oversimplified input options.

SQR CaneSim(Olivier 2001)

SQR Canesim is intended as a more advanced desktop based version of the Internet yield benchmarking DSS. The DSS allows a user to enter an unlimited number of fields, and weather data may be imported whenever required. Additionally, users may keep their own rain gauge and irrigation records that can be used in simulations. A workshop with a number of Extension Officers and scientists was held in March 2004, and a final bug-fix revision was released in November 2004. There are 39 registered SQR Canesim users. Feedback from growers and consultants indicate the use of the DSS for irrigation scheduling, yield forecasting and yield benchmarking.

SASched (Lecler, 2004)

SASched is primarily an irrigation water management tool. It uses the same algorithms as Canesim to describe canopy development and yield, but the description of the water balance is somewhat different. The major difference with Canesim is that SASched is spreadsheet-based. The reason for its development was that it was felt that many farmers find the other tools complex and off-putting to operate, while they are familiar and confident using spreadsheets.

My CaneSim (Singels and Smith, 2004)

The My Canesim system provides the full functionality of the Canesim crop model via the Internet. This has the advantages of centralisation, specifically, more efficient version control and maintenance, as well as the possibility of linking up to industry databases. The model is written in PL/SQL that operates on an Oracle database. Two types of users are envisaged, those who can manage virtual farms with several fields, and those conducting virtual research projects. Further developments envisaged are to promote more intuitive use and to increase execution speed.

A specific application of this system is the provision of simple real-time irrigation advice and yield forecasts to small-scale growers (Singels and Smith, 2004). The system uses real time weather data to estimate the amount of soil water available to the crop in each field of sugarcane and determines whether irrigation should continue, be stopped, or be resumed. Advice is automatically disseminated to individual growers by SMS through the cellular network. The system started during 2004 as a pilot project with eight growers on the Bivane small-scale irrigation scheme in Pongola. Indications are that top yields exceeding 120 t/ha will be achieved, with considerable water savings. The pilot project is being expanded with another 10 growers from the Bivane scheme (totalling 50% of the small scale growers on the Bivane scheme) and six on the Makatini flats irrigation scheme. It is planned to further expand this service and to explore its potential for assisting commercial growers to schedule irrigation with centre pivot systems.

IrriEcon (Singels et al., 1999b)

It is difficult to compare the economic gains from an expensive irrigation system with a less costly system with lower capacity and possible trade-off in yield, or to decide whether to forego irrigation altogether. IrriEcon was designed to be able to compare the economics of

two different irrigation systems using the outputs from Canesim (SQR Canesim, My Canesim or the Internet yield benchmarking system). IrriEcon is used by Extension Officers to help growers decide on the feasibility of upgrading their existing irrigation system, and whether to install an irrigation system on a dryland farm. Output from Canesim runs over several years are taken as input, using two different irrigation scenarios and associated costs. IrriEcon then compares the economics of the simulation runs on a year-by-year basis to help decide the most profitable system. IrriEcon has been used in a number of cases over the past few years to help growers decide on changes to their irrigation system.

Issues for (possible) future developments at SASRI

Technological development

The development of DSSs at SASRI is mainly inducted by research. New research projects are prepared by researchers, on the basis of their own ideas or requests from the industry, e.g. through the extension network. If suitable, the research outcomes are incorporated into CANEGRO. Enhancements that have been found relevant, after several years of testing, can be transferred to Canesim and Canesim based DSSs. Types of enhancements include (i) refinements, to improve model performance for current production situations (potential and water limited growth) and (ii) extensions, to take account of a more comprehensive menu of management options (e.g. fertilisers, different varieties). For obvious reasons, improvements in the user interface and data manipulation (e.g. automatic retrieval of weather data) can be incorporated directly into the DSS.

Until now, the emphasis has been on refinement rather than extension. Further refinements are deemed necessary (Donaldson *et al.*, 2003; Singels *et al.*, 2005), but projects for extension are featuring more prominently. Plans for refinement include:

- Improvement of the description of genotype-by-environment interactions affecting canopy development, biomass accumulation and partitioning at the crop level;
- a more 'nuanced' water uptake algorithm, to enable better assessment of the effects of mild water stress on sucrose accumulation and structural plant growth;
- improvement of the crop forecasting system, among others, by including cane quality. The use of weather forecasts taking account of ENSO events will also be evaluated.

Projects to extend the capabilities of SASRI's models with new management options include:

- Development of an algorithm that represents the green cane harvest trash blanket system by simulating sugarcane trash transformations over time, the effects of trash blankets on the crop and soil water balance, and on canopy development. A first exploration of the potential impact of trash blankets across the South African sugar regions used the Australian APSIM model (van Antwerpen *et al.*, 2002).
- Incorporation of a nitrogen-balance into the CANEGRO model. This submodel will have to take account of major N fluxes and transformations, such as fertiliser application, ammonia volatilisation, effects of harvest residues (trash, green tops), leaching, and the relationship between N-uptake and growth processes.
- Inclusion of an option to assess the effects of ripener application.

There are unlimited possibilities for further developments. These could include for example:

- Further refinements regarding the description of cane quality (RV), the effects of row spacing, the effects of soil compaction or waterlogging on sugarcane growth, and the functional balance between root and shoot growth.
- Inclusion of additional management practices such as P and K fertilisation, green manuring and the application of anti-flowering agents.
- Coupling or merging of crop models with economic models, environmental impact models and/or expert systems such as the trashing economics DSS (Wynne and Van Antwerpen, 2004), the weed control DSS Ukhulacane (Bezuidenhout *et al.*, 2001) or the DSS for variety optimization (Redshaw and Bezuidenhout, 2003).
- Development of a system for exploratory studies, e.g. to contribute to the calculation of the potential for alternative sugarcane products or bio-energy production in South Africa or globally.

Addressing DSS acceptance and utilisation

No systematic survey has been done so far to evaluate the DSS developed at SASRI in terms of adoption by Extension Officers, consultants, farmers and millers. However, the (scattered) data available suggest that DSS uptake and utilisation are much lower than what is possible and desirable. This problem is not restricted to South Africa or sugarcane (Cox, 1996; McCown, 2002a,b; Stephens and Middleton, 2002c)², nor even to agriculture. An analogue to this problem at a much larger scale was recognised more than 30 years ago - and still persists - in business and industry McCown (2002a).

A first step to solve this problem in the context of SASRI DSSs, must be to investigate the actual use of the tools developed and the factors that inhibit (or enhance) their adoption. This could be done by market surveys, for example using the widely acknowledged Technology Acceptance Model (TAM), proposed by Davis (1989). The TAM considers two major causal pathways that determine adoption and use of new technologies: (i) their perceived utility (PU) and (ii) their perceived ease of use (PEOU). PU is the extent to which a person believes that using a certain technology will increase his/her performance, e.g. by making better informed decisions resulting in cost savings, increased production and/or reduced time pressures. PEOU is the extent to which a person believes that learning and applying the technology will be free from effort. According to the TAM, PU and PEOU can be assessed by questionnaires, which can easily be adapted to different technologies or software being considered for acquisition. The TAM has been used extensively to assess information technology acceptance and usage of e.g. on-line learning (Saadé and Bahli, 2005), internet banking (Lai and Li, 2005) and innovations in the dairy sector (Flett *et al.*, 2004); but not for the assessment of DSS using crop models. As a first test of its potential appropriateness for such assessments, a list of reasons for poor adoption of model based DSSs in agriculture, assembled from Stephens and Middleton (2002c), was compared with the concepts of PU and PEOU. The results are presented in Table 1, and show that all but two cases can easily be related to PU and/or PEOU.

The first four and the last two factors mentioned in Table 1 are underlying causes for poor adoption. Most frequently mentioned is the lack of participation of potential beneficiaries prior to and during the development of the DSS (Meinke *et al.*, 2001; Matthews *et al.*, 2002). Frequent and intensive user involvement would at least increase the likelihood of better PUs and PEOUs. Experiences reported by Meinke *et al.* (2001) and Timlin *et al.* (2002) confirm

² In fact, South African sugarcane DSSs were relatively frequently quoted in Matthews and Stephens (2002) as examples of useful applications.

this view. The most outstanding and best-documented example is FARMSCAPE, a participatory action research project which profoundly changed decision making among dryland farmers and their industry advisors in the grain/cotton region of northeast Australia (Carberry *et al.*, 2002).

Table 1. Reasons for poor adoption of model based DSS in agriculture, mentioned by Stephens and Middleton (2002c), and their relationship with perceived utility (PU) and perceived ease of use (PEOU) of the technology acceptance model of Davis (1989).

Reasons for poor adoption of DSS	Low PU	Low PEOU
Unclear definition of clients/end-users	+	+
No end-user input prior to or during the development of the DSS	+	+
Inappropriate focus on scientific issues	+	+
Questions are asked in the wrong way	+	+
DSS does not solve the problems that client is experiencing	+	
DSS does not match their decision-making style		+
Producers do not trust the output due to lack of understanding of the underlying theories of the models utilised	+	
Producers see no reason to change current management practices	+	
DSS does not provide benefit over current decision-making system	+	
Limited computer ownership amongst producers		+
Lack of field testing	+	
Cannot access the necessary data input		+
Lack of technical support		+
Lack of training		+
Poor user interface		+
Poor marketing	?	?
Poor dissemination	?	?

The benefits of farmer/advisor/researcher participation also seem to be confirmed by the enthusiasm of the farmers participating in SASRI's My Canesim SMS irrigation advice pilot scheme. At SASRI, this is so far the project with the highest degree of interaction between developers and beneficiaries. Another clue that seems to appear from this project is that part of its success may be attributable to the fact that the farmers, who are the primary beneficiaries of the DSS, are not the ones who operate the system. This is also in line with the findings of Carberry *et al.* (2002) in the FARMSCAPE project, which eventually resulted in the establishment of a commercial training and accreditation programme in model use.

An additional advantage of the participatory approaches advocated is that frequent and intensive interaction between researchers, farmers and advisors would also help to enhance the practical relevance of the research agenda without compromising scientific rigour. Hence an upward spiral may be set into gear of more industry-relevant on-farm research, improved models and DSS, improved assessment of management opportunities, more successful implementation, and early detection of new industry-relevant research opportunities (Carberry, 2001; Carberry *et al.*, 2002; McCown *et al.*, 2002). In this integrated approach, model development and application could generate a spin-off which goes beyond the direct DSS beneficiaries and which, if properly valued, would co-justify the development costs. The question remains whether the very high (and costly) degree of interaction of the FARMSCAPE approach is always necessary, or whether more modest approaches can also be successful. Bristow and Keating (2003), reporting on the experience from a 'lighter'

collaborative research approach for the Australian sugar sector, concluded that real progress towards improved systems requires a redoubling of efforts to engage with the human aspects of these systems.

Developers of DSSs may become more sensitive to the requirements of potential users, and the upcoming generation, which has literally grown up with computers, may have different perceptions regarding usefulness and ease of use of DSSs than the diminishing group of those who have not. Farmers in such scenarios will use DSSs at their homes for certain applications, but it seems highly unlikely that they will have the time to learn and understand all implications of the results of crop growth models. The mature phase in DSS development for farming may be within reach: Analogous to their complementary role in research, crop growth models in DSS will add value to the role of Extension Officers and consultants, allowing the replacement of much of the 'gut feeling' and generalised rules of thumb with farm-specific hard data. It would be naïve though, to assume that computer models will ever replace their expertise overseeing the full complexity of farming, let alone the human dimension.

Conclusions

Crop growth models are powerful tools in agricultural decision support at the operational, strategic and exploratory levels. Arrested development in an ever more competitive environment will be the medium-term consequence of not developing and applying them.

Prime conditions for utilising the full potential of crop growth models in decision support are that model developers better understand (i) the need for support in agricultural decision-making and (ii) the willingness and capacity of envisaged users to absorb this technology.

Models can play an important role in the interface between farmers, researchers and advisors in participatory research approaches where agricultural research, model development and testing, and application of model-based DSSs can be mutually enhancing.

A possible prime future role of crop models in DSSs for farming is to add value to the role of Extension Officers and consultants by replacing much of the gut feeling and rules of thumb by farm-specific data, and **not** to attempt to replace their expertise overseeing the full complexity of farming.

Acknowledgements

Inspiration for this paper was gained over a number of semi-structured interviews with SASRI researchers and advisors. Thanks are also due to Abraham Singels and Matthew Jones for their constructive review of earlier versions of the paper.

REFERENCES

- Ahuja LR, Ma L and Howell TA (2002). *Agricultural Systems Models in Field Research and Technology Transfer*. CRC Press, Boca Raton.
- Bezuidenhout CN (2004). The predictability of cane production in the South African sugar industry using seasonal climate outlooks and the CANESIM yield forecasting system. *Proc S Afr Sug Technol Ass* 78: 65-68.

- Bezuidenhout CN and Singels A (2001). The use of simulation crop modelling to forecast sugarcane yield. Proceedings of the SASTA workshop on burn/harvest to crush delays and crop estimating. 8 November 2001, Mount Edgecombe, South Africa. pp 20-29.
- Bezuidenhout CN and Singels A (2003). How accurate are Canesim estimates of sugarcane production? *Proc S Afr Sug Technol Ass* 77: 596-600.
- Bezuidenhout CN, Leibbrandt NB and Raja A (2001). The development of a computerised decision support tool for weed control in the South African sugar industry. Proceedings of the World Congress of Computers in Agriculture and Natural Resources. 13-15 March 2002, Iguacu Falls, Brazil. pp 642-650.
- Bezuidenhout CN, Singels A and Hellmann D (2002). Whole farm harvesting strategy optimisation using the CANEGRO model: A case study for irrigated and dryland sugarcane. *Proc S Afr Sug Technol Ass* 74: 250-259.
- Boote KJ, Kropff MJ and Bindraban PS (2001). Physiology and modelling of traits in crop plants: Implications for genetic improvement. *Agric Systems* 70: 395-420.
- Bouman BAM, van Keulen H, van Laar HH and Rabbinge R (1996). The 'School of de Wit' crop growth simulation models: A pedigree and historical overview. *Agric Systems* 52: 171-198.
- Bristow KL and Keating BA (2003). Systems analysis and modeling in sugar research: Reflections on the CRC Sugar experience. *Proc Aust Soc Sug Cane Technol* 25 [CD ROM].
- Brüggemann EA, Klug JR, Greenfield PL and Dicks HM (2001). Empirical modelling and prediction of sugarcane yields from field records. *Proc S Afr Sug Technol Ass* 75: 204-210.
- Buringh P, van Heemst HDJ and Staring GJ (1975). Computation of the absolute maximum food production of the world. Wageningen Agricultural University, Wageningen, The Netherlands.
- Carberry PS (2001). Can science rigor and industry relevance both be achieved in participatory action research? *Agric Science* 14(3): 25-31.
- Carberry PS, Hochman Z, McCown RL, Dalgliesh NP, Foale MA, Poulton PL, Hargreaves JNG, Hargreaves DMG, Cawthray S, Hillcoat N and Robertson MJ (2002). The FARMSCAPE approach to decision support: Farmers', advisors', researchers' monitoring, simulation, communication and performance evaluation. *Agric Systems* 74: 141-177.
- Cheeroo-Nayamuth BF and Nayamuth ARH (2000). Preliminary testing of the CANEGRO-DSSAT V3.5 model in Mauritius. pp In: GJ O'Leary and GA Kiker (Eds). Proceedings of the first International Workshop on the CANEGRO sugarcane model, 4-7 August 2000. Mount Edgecombe, South Africa. pp 17-19.
- Cheeroo-Nayamuth BF and Nayamuth ARH (2001). Climate change and sucrose production in Mauritius. *Proc Int Soc Sug Technol Ass* 24(2): 107-112.
- Cheeroo-Nayamuth BF, Robertson MJ, Wegener MK and Nayamuth ARH (2000). Using a simulation model to assess climatically-determined sugarcane yield in Mauritius. *Field Crops Res* 66: 225-243.
- Cox PG (1996). Some issues in the design of agricultural decision support systems. *Agric Systems* 52: 355-381.
- Davis FD (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly* 13: 319-339.
- de Lange J and Singels A (2003). Using the internet-based Canesim model for crop estimation in the Umfolozi mill supply area. *Proc S Afr Sug Technol Ass* 77: 592-595.
- Donaldson RA, Redshaw KA and Singels A (2003). In search of parameters to model cultivar-specific canopy development. *Proc S Afr Sug Technol Ass* 77: 605-609.

- Everingham YL, Muchow RC, Stone RC, Inman-Bamber NG, Singels A and Bezuidenhout CN (2002). Enhanced risk management and decision-making capability across the sugarcane industry value chain based on seasonal climate forecasts. *Agric Systems* 74: 459-77.
- Flett, R, Alpass F, Humphries S, Massey C, Morriss S and Long N (2004). The technology acceptance model and use of technology in New Zealand dairy farming. *Agric Systems* 80: 199-211.
- Goudriaan J (1996). The end of modelling? In: A Stein, FWT Penning de Vries and PJ Schotman (Eds). *Models in action*. Proceedings of a seminar series 1995/1996. CT de Wit Graduate School for Production Ecology (Quantitative approaches in systems analysis; no 6). Wageningen, The Netherlands. pp. 115-120.
- Hammer GL, Kropff MJ, Sinclair TR and Porter JR (2002). Future contributions of crop modelling - from heuristics and supporting decision making to understanding genetic regulation and aiding crop improvement. *Europ J Agron* 18: 15-31.
- Inman-Bamber NG (1991). A growth model for sugarcane based on a simple carbon balance and the CERES-Maize water balance. *S Afr J Plant Soil* 8: 93-99.
- Inman-Bamber NG (1995). Climate and water as constraints to production in the South African sugar industry. *Proc S Afr Sug Technol Ass* 69: 55-59.
- Inman-Bamber NG, Lisson, SN, McGlinchey M, Singels A and Bristow KL (2001). Sugarcane simulation: State of the art, applications and implications. *Proc Int Soc Sug Cane Technol* 24(2): 113-117.
- Keating BA, Verburg K, Huth NI and Robertson MJ (1997). Nitrogen management in intensive agriculture: Sugarcane in Australia. pp 221-242 In: BA Keating and JR Wilson (Eds). *Intensive sugarcane production: Meeting the challenges beyond 2000*. CAB International, Wallingford, USA.
- Kropff MJ, Jones JW and van Laar HH (Eds) (2001). Advances in systems approaches for agricultural development. *Agric Systems* 70 (Special Issue): 353-640.
- Lai VS and Li H (2005). Technology acceptance model for internet banking: an invariance analysis. *Information and Management* 42: 373-386.
- Lecler NL (2004). Sasched: A water conservation and demand management tool for irrigated sugarcane. Paper presented at the South African National Committee on Irrigation and Drainage Conference (SANCID-2004).
- Leffelaar PA (1993). Basic elements of dynamic simulation. pp 11-27 In: PA Leffelaar (Ed). *On systems analysis and simulation of ecological processes*. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Lisson SN, Brennan, L, Bristow KL, Schuurs M, Linedale A, Smith M, Hughes D and Keating BA (2000). DAM EASY - A framework for assessing the costs and benefits of on-farm storage based sugarcane production systems. *Proc Aust Soc Sug Cane Technol* 22: 186-193.
- Matthews R (2002). Crop management. pp 29-53 In: R Matthews and W Stephens (Eds), *Crop-soil simulation models: Applications in developing countries*. CABI International, Wallingford, USA.
- Matthews R, Stephens W, Hess T, Middleton T and Graves A (2002). Applications of crop/soil simulation models in tropical agricultural systems. *Advances in Agronomy* 76: 32-124.
- McCown RL (2002a). Locating agricultural decision support systems in the troubled past and socio-technical complexity of 'models for management'. *Agric Systems* 74: 11-25.
- McCown RL (2002b). Changing systems for supporting farmers' decisions: Problems, paradigms and prospects. *Agric Systems* 74: 179-220.

- McCown RL, Keating BA, Carberry PS, Hochman Z and Hargreaves D (2002). The co-evolution of the agricultural production systems simulator (APSIM) and its use in Australian dryland cropping research and farm management intervention. pp 149-175 In: LR Ahuja, L Ma and TA Howell (Eds). *Agricultural systems models in field research and technology transfer*. CRC Press, Boca Raton, USA.
- McGlinchey MG and Inman-Bamber NG (1996). Predicting sugarcane water use with the Penman-Monteith equation. pp 592-598 In: CR Camp, EJ Sadler and RE Joder (Eds), *Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling*. San Antonio, ASEA, St Joseph, Michigan, USA. 3-6 November 1996.
- Meinke H, Baethgen WE, Carberry PS, Donatelli M, Hammer GL, Selvaraju R and Stöckle CO (2001). Increasing profits and reducing risks in crop production using participatory systems simulation approaches. *Agric Systems* 70: 493-513.
- Olivier FC (2001). SQR-CANESIM User's Manual. Irrigation scheduling and yield prediction software for sugarcane (Windows version 2004 revised by MT Smith). South African Sugar Association Experiment Station, Mount Edgecombe, South Africa.
- Parry ML, Rosenzweig C, Iglesias A, Livermore M and Fischer G (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* 14: 53-67.
- Redshaw KA and Bezuidenhout CN (2003). Decision support for optimal variety selection on a farm scale for South African sugarcane growers. ISSCT agronomy workshop, MSIRI, Réduit, Mauritius, 21-21 July 2003.
- Saadé R and Bahli B (2005). The impact of cognitive absorption on perceived usefulness and perceived ease of use in on-line learning: An extension of the technology acceptance model. *Information and Management* 42: 317-327.
- Sinclair T and Seligman NG (1996). Emerging maturity or arrested development in crop modeling? pp 93-103 In: A Stein, FWT Penning de Vries and PJ Schotman (Eds). *Models in action. Proceedings of a seminar series 1995/1996*. CT de Wit Graduate School for Production Ecology (Quantitative approaches in systems analysis; no 6). Wageningen, The Netherlands,
- Singels A and Bezuidenhout CN (2002). A new method of simulating dry matter partitioning in the Canegro sugarcane model. *Field Crops Res* 78: 151-164
- Singels A and Donaldson RA (2000). A simple model of unstressed sugarcane canopy development. *Proc S Afr Sug Technol Ass* 74: 151-154.
- Singels A and Smith MT (2004). Improving irrigation water use efficiency of small-scale sugarcane production by real-time scheduling advice using weather data, a web based crop mode, and cellular technology: Preliminary results. Paper presented at the South African National Committee on Irrigation and Drainage Conference (SANCID-2004).
- Singels A, Donaldson RA and Smit MA (2005). Improving biomass production and partitioning in sugarcane: theory and practice. *Field Crops Res* (in press).
- Singels A, Kennedy AJ and Bezuidenhout CN (1998). IRRICANE: A simple computerised scheduling method for sugarcane. *Proc S Afr Sug Technol Ass* 72: 117-122.
- Singels A, Kennedy AJ and Bezuidenhout CN (1999a). Weather based decision support through the Internet for agronomic management of sugarcane. *Proc S Afr Sug Technol Ass* 73: 30-32.
- Singels A, Bezuidenhout CN and Schmidt EJ (1999b). Evaluating strategies for supplementing irrigation of sugarcane in South Africa. *Proc Aust Soc Sug Cane Technol* 21: 1-8.
- Stephens W and Middleton T (2002a). Tools to support operational decision making. pp 105-225 In: R Matthews and W Stephens (Eds). *Crop-soil simulation models: Applications in developing countries*. CABI International, Wallingford, USA.

- Stephens W and Middleton T (2002b). Tools to support strategic decision making. pp 117-127 In: R Matthews and W Stephens (Eds). *Crop-soil simulation models: Applications in developing countries*. CABI International, Wallingford, USA.
- Stephens W and Middleton T (2002c). Why has the uptake of Decision Support Systems been so poor? pp 129-147 In: R Matthews and W Stephens (Eds). *Crop-soil simulation models: Applications in developing countries*. CABI International, Wallingford, USA.
- Ten Berge HFM and Stein A (Eds) (1997). *Model-based decision support in agriculture*. CT de Wit Graduate School for Production Ecology (Quantitative approaches in systems analysis; no. 15). Wageningen, The Netherlands.
- Thorburn PJ, Horan, HL Biggs IM and Park SE (2004). Which is the most important crop when assessing nitrogen applications – The next or the last? *Proc S Afr Sug Technol Ass* 78: 383-392.
- Timlin DJ, Pachepsky Y, Whisler FD and Reddy VR (2002). Experience with on-farm applications of GLYCIM/GUICS. pp 55-69 In: LR Ahuja, L Ma and TA Howell (Eds). *Agricultural systems models in field research and technology transfer*. CRC Press, Boca Raton, USA.
- Tsuji GY, Hoogenboom G and Thornton PK (Eds) (1998). *Understanding options for agricultural production*. (Systems Approaches for Sustainable Agricultural Development 7). Kluwer Academic Publishers, Dordrecht, The Netherlands.
- van Antwerpen R, Thorburn PJ, Horan H, Meyer JH and Bezuidenhout CN (2002). The impact of trashing on soil carbon and nitrogen: II: implications for sugarcane production in South Africa. *Proc S Afr Sug Technol Ass* 76: 269-280.
- van den Berg, M., 2000. Application of a summary crop growth model for quantified land evaluation. In: *Land use systems research on strongly weathered soils in south and south-east Brazil*. The Royal Dutch Geographical Society/Faculty of Geographical Sciences (Netherlands Geographical Studies 271). Amsterdam/Utrecht, The Netherlands. pp 185-197.
- van Diepen, CA and van der Wal T (1995). *Crop growth monitoring and yield forecasting at regional and national scale*. Publication EUR 16008 EN of the Office for Official Publications of the EC, Luxembourg, Belgium. pp 143-158.
- van Ittersum MK and Donatelli M (Eds) (2003). Modelling cropping systems: science, software and applications. *Europ J Agronomy* 18(4) (Special Issue): 187-393.
- van Laar HH and Goudriaan J (Eds) (1997). *SUCROS97: Simulation of crop growth for potential and water-limited production situations. As applied to spring wheat*. Institute for Agrobiological and Soil Fertility/CT de Wit School for Production Ecology (Quantitative approaches in systems analysis 14). Wageningen, The Netherlands.
- Wynne AT and van Antwerpen R (2004). Factors affecting the economics of trashing. *Proc S Afr Sug Technol Ass* 78: 207-214.