Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future

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Mathematical simulation of crop growth and water relations has become indispensable to agricultural science and practice. A critical assessment of how modelling has contributed to the development of crop science and to the management of crop production and natural resources in South Africa (SA) over the past 25 years could give new perspectives on the benefits derived from modelling, the appropriateness of approaches employed and the best way forward. The initial objectives of the major SA modelling initiatives (ACRU, BEWAB, CANEGRO, CERES, PUTU, SAPWAT, SWB) dictated the approaches that were followed and determined their impacts. Significant advances were made with regard to improved understanding of crop growth and water use and adapting models for local conditions such as dryland grain crop production under very low rainfall. Modelling provided invaluable support for strategic investigations into the impacts of climate change, land use and water use. Many of the models succeeded in providing much-needed information to improve tactical and operational management of irrigated and dryland agriculture. Some models have been (and are being) used operationally to forecast crop production (maize, wheat and sugar) and to monitor droughts in natural vegetation, adding value to the respective industries. Modelling has formed, in some cases, an integral part of tertiary education in crop science and hydrology. This should be strengthened to build more capacity to address the ever-increasing complexity of challenges in agriculture. The review identified factors that are crucial for modelling to maintain effective impacts on the science and practice of crop production and natural resource use. These were excellent scientific leadership, long term funding, effective collaboration between local and with international groups, expertise on local agronomy and high quality experimental data for model testing and adaptation. Future modelling efforts should explore opportunities to integrate information obtained from technologies such as remote sensing and genomics.

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Introduction

Crop modelling may be defined as the construction of mathematical analogues of the cropping system and their use in dynamic simulation of constituent processes by numerical integration with the use of computers (adapted from Sinclair & Seligman, 1996; Hammer, 1998). Crop modelling has developed extensively over the past 40 years in parallel with advances in crop and environmental sciences and in computing technologies. A wide range of crop models exist, encompassing different approaches and levels of complexity and emphasising different aspects of the soil-plant-atmosphere system (for example Jones *et al*., 2003; Keating *et al*., 2003; Stöckle *et al*., 2003). Different approaches to modelling and their advantages and limitations have been reviewed by Passioura (1996), Monteith (1996) and Boote *et al*. (1996).

A distinction is generally drawn between a functional and a mechanistic approach (for example Wagenet, 1988; Passioura, 1996). The former could be seen as an engineering approach to solving problems (prediction) and the latter as a scientific approach to discovering knowledge (understanding). Hammer (1998) warns against a strong separation between the two approaches and argues that dealing simultaneously with understanding and prediction enhances capability on both fronts. In reality, many crop models contain aspects of both approaches and often serve both purposes, although the emphasis could vary. Boote *et al*. (1996) group potential uses of models under support for (1) research, (2) crop management and (3) policy analysis. Models can be used to integrate knowledge and data across disciplines, assisting the synthesis of new knowledge. Models also enable scientists to examine scientific hypotheses and investigate the impact of unprecedented agricultural and ecological conditions. Management applications correspond broadly to the types of decision-making, viz. strategic, tactical and operational. Strategic decisions are high level decisions (planning, policy formulation) with long-term outcomes, such as analysing the impact of land use and climate change on resource sustainability and agricultural productivity. Tactical decisions, such as choice of cultivar, plant density and fertiliser amount and type are typically made before the start of a growing season and will have an effect throughout the season. Operational decisions such as irrigation scheduling and weed control are taken on a day to day basis.

A large body of literature shows that mathematical simulation of crop growth and crop water relations has become indispensable to agricultural science and practice. Crop growth models are ideal for the diagnosis of the effects of both prevailing and extreme circumstances and the prognosis of the effects of future events. They are formidable in predicting crop performance and resource dynamics and thus provide excellent information for planning and management decisions over both the long and short term.

A critical assessment of how modelling has contributed to the development of crop science and to the management of crop production and natural resources in South Africa (SA) over the past 25 years could give new perspective and provide answers to the following questions. Firstly, has model development and application in SA made a significant, innovative contribution to the science internationally? Secondly, were resources for crop modelling applied efficiently and was the benefit derived worth the effort? Finally, were approaches, technology and methods used appropriately and are there opportunities to improve?

The overall objective of this paper is to review the development of water balance and crop modelling and its impacts on SA crop production. More specifically, the paper highlights key characteristics and achievements of major SA modelling initiatives, and assesses their impacts on (1) improving the sustainability and efficiency of SA crop production, and (2) enhancing the science of crop production. It also identifies key factors necessary for successful crop and water balance modelling, and suggests opportunities for future model development and application.

The focus of this paper is predominantly on deterministic (as opposed to stochastic) and physically-based (as opposed to empirical) modelling of growth, production and water balance of crops, pastures and rangelands.

The history and achievements of major modelling projects

ACRU

ACRU is a process-based agrohydrological model and has its origins in the early 1970s with a distributed, catchment–based, hydrological study in the KwaZulu-Natal Drakensberg (Schulze, 1975). The agricultural component of ACRU came to the fore during research on an agrohydrological and agroclimatological atlas for Natal (Schulze, 1983). Since then the model has developed, through co-operation with many partners, to its present status as an integrated modelling system.

ACRU is a multi-purpose model that integrates the various water budgeting components of the terrestrial hydrological system (Schulze, 1995a and updates). It can be applied to crop yield modelling, runoff estimation, design hydrology, reservoir yield simulation, ecological water requirements, irrigation water demand and supply, water resources assessment, planning optimum water resource utilisation and allocation, conflict management in water resources and the assessment of climate-change and land-use impacts.

The model utilises a multi-layer soil water budget for calculating evapotranspiration. Yields for maize, wheat (Domleo, 1990; Schulze *et al.*, 1995b), sugarcane (using the Thompson 1976 concepts; refined by Hughes, 1992; Lumsden *et al.*, 1998) and primary production (Schulze, 1984) are calculated using either physically based or empirical functions of evapotranspiration or transpiration, depending on availability of data, that take into account crop development stage, thus reflecting the strong observed link between yield and water use for most crops.

ACRU has been designed as a multi-level model, with multiple options or alternative pathways available in many of its routines, depending on the level of input data available, or the detail of output required. ACRU can operate as a point model, or as a lumped small area model (i.e. field, farm or relatively uniform small catchment), on large catchments or at national scale, the latter two by interlinking homogeneous sub-catchments hydrologically from upstream to downstream (Schulze, 1995a).

From both hydrological and agricultural perspectives, ACRU has been tested comprehensively against observed data in South Africa as well as elsewhere in Africa, the USA and Europe (e.g. reviews by Schulze, 1995a; 2008), and has been applied in a range of agriculture and water resource assessments in South Africa and elsewhere since the mid-1980s. Schulze and Smithers (2004) as well as Schulze (2007a) have reviewed ACRU tests and applications in detail. Selected examples are: risk analysis and optimisation of crop irrigation (Schulze, 2007a); determination of crop water and irrigation requirements (Schulze, 2007a); quantifying downstream impacts of irrigated crop production (Kienzle *et al.*, 1997; Schulze *et a*l., 1998); quantifying land use impacts (e.g. Kienzle *et al.*, 1997); optimisation of maize planting dates (Schulze, 2003); assessing the impacts of climate change on hydrology and crop production (Schulze, 2007b; Schulze *et al.*, 2007); quantifying country wide yield potential and variability for maize and natural veld (Schulze, 2003; Schulze, 2007a); sugarcane (Lumsden *et al.*, 1999) and maize (Schulze, 2003) crop forecasting.

The ACRU model lends itself excellently to use as a teaching tool as it simulates processes in the soil-plant-atmosphere continuum based on hydrological and hydraulic principles, and because it is extensively documented in text book style (Schulze, 1995; Schulze & Smithers, 2004; Smithers & Schulze, 2004). In the School of BEEH at UKZN an introductory modelling course focusing on ACRU is compulsory for hydrology and agricultural engineering undergraduate students, and is optional for agriculture students. It is also applied in a dam design course and in other hydrology modules (e.g. forest hydrology, climate change). An advanced ACRU course is given at hydrology honours level, with links also to databases, GIS and to fieldwork. Short professional courses on the ACRU system are given in SA to consultants, and on request to sector specific users, e.g. South African Department of Water Affairs and Forestry (DWAF). International courses on ACRU are given on request/invitation to research/academic institutions and to date courses have been held in Kenya, Germany, France and Sweden.

User documentation on ACRU has been published periodically since 1984 (Schulze, 1984) but the seminal work on model background, theory and concepts is that by Schulze (1995a; 552 pages), while operating procedures are contained in a user manual edited by Smithers and Schulze (2004; 302 pages). Both publications are now available online from *www.beeh.unp.ac.za/acru*. A restructured modular version of the ACRU system using a Java-based object-oriented design methodology was completed around the year 2000 and is described in detail, for example, by Clark *et al.* (2001) and by Kiker *et al.* (2006). A salinity module has been added (Teweldebrhan *et al.*, 2003) and ACRU's nitrate and phosphorus modules first developed for application in the USA and SA (Campbell *et al.*, 2002) are currently being revised (Lorentz, 2008 pers. comm.).

BEWAB and SWAMP

Two models were developed by the Soil Science Section of the Department of Soil, Crop and Climate Sciences (DSCCS) at the University of the Free State (UFS), viz. BEWAB and SWAMP. BEWAB is an abbreviation for the Afrikaans term ”BEsproeiingsWAterBestuursprogram", meaning “irrigation water management program”. The model follows a pragmatic approach to assist irrigation farmers with daily decisions regarding the amount and timing of water applications. The model caters mainly for field crops and uses fixed planting dates for the Vaalharts, Sandvet and Riet River irrigation schemes. Upper and lower limits of plant available water for different soils are estimated from textural properties (i.e. silt-plus-clay content). Built into the model are crop water production functions and non-linear crop water demand functions for different crops and planting dates for each locality, based on water use measurements (Bennie *et al.*, 1988). The procedure was modified by Bennie *et al.* (1997) to account for the effect of water stress on growing season length. Crop water demand functions were also divided into four linear stages following the major growth stages defined by Smith (1992). The empirical nature of model was addressed by Strydom (1998), who introduced the universal transpiration efficiency theory and concepts developed by De Wit (1958), Hanks (1983) and Tanner and Sinclair (1983). Consequently, the model can now be applied on any irrigation scheme if the inputs regarding harvest index, maximum biomass yield and maximum evapotranspiration are available for the location concerned. The software suggests appropriate values for these inputs for different locations. Irrigation schedules also take into account two types of irrigation, viz. sprinkler and flood as described by Bennie *et al.* (1988)

The scientific approach is further explained by Bennie *et al.* (1988), Van Rensburg (1988), Van Antwerpen (1988), Bennie (1995), Strydom (1998) and Van Antwerpen (1998). The model was scientifically evaluated by Van Rensburg *et al.,* (1995), Bennie *et al.* (1997) and Van Rensburg *et al.* (2003). Features of the model that users seem to find attractive are its user friendliness and the efficacy of its proposed irrigation schedules. Sales records show that more than 500 farmers, extension officers and consultants have bought the program since 1988. It is also used as an educational tool in undergraduate and post-graduate water management courses. The program was recently upgraded by Van Rensburg and Zerisghy (2008) by incorporating new research findings and converting the programming code from DOS based GWBasic to Windows based VisualBasic6 (Microsoft Corp.). This enabled significant improvements to processing efficiency and user friendliness.

The motivation for developing another model, SWAMP i.e. “soil water management programme”, arose from the need to integrate available knowledge on the water balance components related to dryland farming (Bennie *et al.*, 1998). Before the model was constructed, different water balance algorithms were selected from literature and then evaluated against experimental data obtained from tillage experiments conducted at various locations in the Free State province (Bennie *et al.*, 1994). The procedures that performed the best were included in the SWAMP model, viz. Ritchie (1972) for evaporation, and the Philip (1957) as well as Green and Ampt (1911) procedures for runoff. Unfortunately, none of the runoff procedures performed well. A new procedure for estimating deep percolation has been developed, but has not yet been tested. The procedure is based on *in situ* drainage curves determined according to the method of Ratliff *et al.* (1983).

Although SWAMP was meant to be a pragmatic model to support operational management, users perceive it to be more of an analytical tool to support tactical management. A valuable aspect of the model is that it provides estimates of the amount of water that will be stored in the soil during fallow periods. It also gives insight into water conservation processes so that tillage practices can be optimised accordingly. The model estimates, with reasonable accuracy, evapotranspiration from maize, wheat, sorghum and sunflower using different tillage systems on different soil/climate combinations. Another strong point is the model's ability to estimate changes in the soil water content of the root zone. Such information can be used to optimise agronomic practices.

Potential users of the model require hands-on training and should have a basic knowledge of the crop water balance processes. Feedback from users suggests that the user friendliness can be improved. On the technical side the runoff procedure should be improved. There is also a need to adapt the model for use with water conservation systems such as in-field rainwater harvesting. Adaptations to cope with root zone salinity management at farm scale are also needed, i.e. the development of subroutines for salt balances. The principal researcher responsible for maintaining and improving both the SWAMP and BEWAB models is Prof. L.D. Van Rensburg of DSCCS at UFS.

CANEGRO and CANESIM

CANEGRO was developed in response to questions from SA Sugar Industry stakeholders. The intention was to model the most relevant physiological processes in a mechanistic way. The outbreak of the sugarcane stalk borer (*Eldana saccharina*) in SA focused attention on the influence of harvest age on productivity. *E. saccharina* proliferated when sugarcane was cut older than 12 months (Atkinson *et al.*, 1981) and there was a need to quantify the impact of reducing harvest age to limit its damage. Processes of canopy development, biomass accumulation and partitioning, particularly in ageing crops, appeared to be fundamental to the understanding of optimum harvest age.

Biomass accumulation equations for sugarcane were first evaluated by Inman-Bamber and Thompson (1989) and a working sugarcane growth model was first described by Inman-Bamber (1991). The model simulated the development of leaves on the primary shoot using thermal time. The tillering processes was conceptualised as series of cohorts emerging in concert with leaves on mother shoots (Inman-Bamber, 1994). This provided the foundation for calculated leaf area index and consequently the interception of radiation. Bezuidenhout *et al.* (2002b) suggested improvements to the simulation of leaf and tiller development to account for the effect of crop class, final stalk population and light on tiller and leaf appearance and senescence.

Biomass accumulation was calculated by converting intercepted radiation to gross assimilate and then deducting maintenance and growth respiration based on the work of McCree (1970) and Hesketh *et al.* (1971). Biomass partitioning to different plant organs was calculated using empirical equations to account for age or total biomass. Sucrose content in the stalk was calculated using empirical functions of age, time of year and water stress. Singels and Bezuidenhout (2002) improved the simulation of biomass partitioning by adding algorithms based on source-sink processes to calculate partitioning to roots, leaves and stalk sucrose. The partitioning of stalk biomass between sucrose and fibre was now driven by radiation, temperature and water stress.

Emphasis was placed on simulating water stress accurately and the Ceres-Maize (Jones & Kiniry, 1986) concepts of water stress were refined and calibrated for sugarcane. Considerable effort was also expended on the development of an appropriate Penman-Monteith (PM) method for determining atmospheric evaporative demand to account for canopy characteristics of sugarcane (Inman-Bamber *et al*., 1993; McGlinchey & Inman-Bamber, 1996a; 1996b).

CANEGRO was developed primarily as a tool to direct and assist research (Inman-Bamber, 1995c) and application was limited to studies by scientists who had direct access to the code. Examples of these applications are: scheduling and management of irrigation (McGlinchey *et al.,* 1995; McGlinchey & Inman-Bamber, 1996b; Inman-Bamber *et al.,* 1993); crop forecasting (McGlinchey, 1999); determination of potential and attainable yield (Inman-Bamber, 1995b); optimising harvest age (Inman-Bamber, 1994; Bezuidenhout *et al*., 2002a); and consultation studies for farmers and millers to estimate (1) climatic yield potential, (2) yield loss due to mill shutdowns and interruptions in irrigation water supply, and (3) the impact of changing milling season length on productivity.

CANEGRO was given international recognition by its incorporation in the DSSAT v3.1 (Inman-Bamber & Kiker, 1997) and v4.5 (Jones *et al*., 2007) packages. The model is now being used and further developed by the International Consortium for Sugarcane Modelling (*http://sasex.sasa.org.za/misc/icsm.html*)

The CANESIM model was developed with the aim of making sugarcane modelling accessible to a wider user base. The focus was on simplifying the inputs required for running the model and on providing a user-friendly interface. It uses a single layer soil module and a thermal time driven canopy cover development (Singels & Donaldson, 2000), thereby circumventing the need for (1) detailed input data, and (2) simulation of layer specific water redistribution and extraction and leaf and tiller development. Biomass accumulation and partitioning are simulated as in CANEGRO. A demonstration version of the model (Singels *et al.,* 1999) is available on the Internet (*http://sasri.sasa.org.za/irricane/index.htm*) to calculate crop water use and cane yield for specified SA climates, soils and cropping seasons, either in a hindcast or forecast mode. A later, more powerful version of the model is also available on the Internet to registered users. This model has been used to provide real-time irrigation advice to small-scale and commercial sugarcane farmers (Singels & Smith, 2006). This innovation received international recognition in 2007 in the form of a WATSAVE award from the International Commission of Irrigation and Drainage (*http://www.icid.org*). Singels (2007) also showed how it can be used to assist extension staff to benchmark yields and water use and to address practical problems in the field. The model has also been used operationally for yield forecasts at mill and industry level since 2000 (Bezuidenhout & Singels, 2007a; 2007b).

A model for simulating the effects of a crop residue layer on the growth and water relations of sugarcane crops was developed by Jones and Van den Berg (2006) and will soon be incorporated into the Canesim and Canegro models.

CERES and CROPGRO

The Decision Support System for Agrotechnology Transfer (DSSAT) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Jones *et al*., 1998; Uehara & Tsuji, 1998). Its initial development was motivated by a need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where soils and climate differed. DSSAT is a collection of independent programs that operate together; crop simulation models such as CERES maize (Jones & Kiniry, 1986) and CROPGRO (Jones *et al.,* 1991) are at its core.

In SA the CERES-maize model within DSSAT was first used in the preliminary evaluation of two maize growth-simulation models with SA field data sets, referred to as the Phoenix Project (De Vos & Mallett, 1987). Du Pisani (1987) also evaluated the model's potential for drought assessment in SA. Soybean modelling was initiated with the adaptation of SOYGRO v4.1 to account for the phenological development of local cultivars (Piper *et al*., 1996).

The CERES-maize model was adapted to fit SA conditions. Subroutines were changed to compensate for wider row widths (Du Toit *et al*., 1994c), phenological development (Du Toit *et al.,* 1994b; 1998), prolificacy (Du Toit *et al*., 2000) and genetic parameters (Du Toit *et al*., 1994a; Du Toit, 2002). A water logging subroutine was added (Du Toit *et al.,* 2002) to simulate a fluctuating water table, based on the work by Hensley *et al*., 1996). Data from the national cultivar soybean trials and the Super Soya project were used to validate the CROPGRO model; a yield gap analysis indicated good predictability (Smit, 2000, ARC-GCI, Potchefstroom). Genetic coefficients for 20 SA soybean cultivars have also been determined (Prinsloo & du Toit, 2004).

Estimating maize yield over larger areas has long been the main challenge for CERES-maize in SA, starting with the Losdoorns Project (Prinsloo & Du Toit, 1995). From this, a maize yield modelling framework for the Free State was developed (Van den Berg & Manley, 2000), which later formed the basis of the current National Crop Estimates System for maize. This was derived as part of an internationally funded Ecoregional project (Durand & Du Toit, 2000b; Du Toit, 2003; ISNAR, 2004)) which is currently used to supply the National Crop Estimates Committee with regular forecasts throughout the season. This system incorporates the use of CERES-maize (SA), SA input data and a weather analogue system within a Visual Basic.NET (Microsoft Corp.) shell. The weather analogue model chooses an analogue year to infill the missing data of the current season to enable yield forecasts (Du Toit *et al*., 2001). The weather analogue and a statistical procedure for model validation (Du Toit *et al*., 1997) were incorporated into DSSAT 4.0.

CERES-maize in South Africa has been used to find solutions to problems from farm (Prinsloo *et al*., 1998, Durand & Du Toit, 2000a) to regional scale (Schulze *et al*., 1993; Walker, 2005) and to simulate maize yield for a diverse range of applications such as drought assessment (Du Pisani 1987; De Jager *et al*., 1998) and climate change (Du Toit *et al*., 2000).

The release of DSSAT v4.0 saw major changes to the program, where the basis of the new DSSAT is the Cropping System Model (CSM) with a modular structure (Jones *et al*., 2003). CERES-maize and CROPGRO have now become part of the new CSM. Efforts are currently underway to test the yield simulation ability of the CSM of DSSAT v4.0 with that of CERES-maize (SA) and if necessary incorporate some of the developed subroutines for South African conditions into the new CSM model.

PUTU

The PUTU models evolved from work on leaf photosynthesis in 1968 (De Jager, 1968; De Jager, 1971a; 1971b). The first crop model dates to 1974 (De Jager, 1974; Kaiser & De Jager, 1974), when the name "PUTU", after the South African maize meal porridge, was adopted.

The PUTU system explains and quantifies the growth and development processes of agronomic crops using mathematical equations and the fundamental laws of physics and chemistry. The rationale was that mechanistic, dynamic simulations are analytical, precise and repeatable and hence indispensable for practical agricultural problem solving and management decision support (De Jager *et al*., 2001). Special emphasis is accorded to intra-seasonal and long-term weather perturbations because of their overwhelming controlling influence (De Jager *et al*., 1987).

PUTU started with an attempt to formulate the combined effect of light and temperature on leaf photosynthesis. Mathematical equations were developed for the effect of these factors, as well as water limitation, on the rate of photosynthesis and crop growth. The efficiency of radiation use in photosynthesis was computed and converted to carbohydrate in the first "PUTU" dynamic maize crop growth simulation (De Jager, 1976). Early model theory, definitions and parameter values, for maize, were documented by De Jager and King, (1974) and later for wheat (de Jager *et al*., 1982; Singels & De Jager, 1991c; 1991d; 1991e), potatoes (Rutherfoord & De Jager, 1975) and natural grassland (Fouché, 1992; Howard, 1997). A generic model was developed (De Jager, 1997) for simulating yield and water use of any crop by computing yield response as a function of relative evapotranspiration deficit following Doorenbos *et al*. (1979). Nitrogen sub-models were incorporated and tested in both the wheat (Singels, 1993) and maize (Van Rooyen, 1988) models. A sub-model for simulating wheat grain quality was also developed (Singels, 1993). Various aspects of these models have been validated extensively (De Jager *et al*., 1983; Singels & De Jager, 1991c; 1991d; 1991e; De Jager, 1994; Singels & De Jager, 1995).

These models contained both previously published algorithms (for example Ritchie & Otter, 1985; Jones & Kiniry, 1986; Seligman & Van Keulen, 1981; Doorenbos *et al*., 1979) and newly developed algorithms. Noteworthy concept and computing milestones included: testing hourly (De Jager, 1974) and daily (De Jager *et al*., 1982) iterations and choosing the latter; using an iterative technique to solve non-linear equations for computing crop evaporation under water stress conditions (De Jager & Singels, 1987; De Jager *et al*., 2001); the introduction of bulk crop canopy resistance to water vapour exchange (De Jager & Van Zyl, 1989; Van Zyl *et al*., 1990) and determining its dependence on weather (Van Zyl & De Jager, 1992; Van Zyl & De Jager, 1994); defining relative evaporation rate and using it as a water status growth limiting factor (De Jager, 1974). Later, the factors defined and some of the values reported by Doorenbos *et al*. (1979) were introduced (De Jager, 1997).

The concepts of crop surface conductance (De Jager *et al*., 1974; De Jager *et al*., 1990) and of crop hydraulic conductivity were developed (Van Zyl *et al*., 1981; De Jager *et al*., 1984). The effective soil profile water status was computed by weighting layers according to root density. An initial single layer soil water budget preceded two-layered (De Jager *et al*., 1982) and multi-layered (De Jager *et al*., 2001) models. Algorithms for evaporation from the soil, deep percolation and vertical soil water movement were added. The most effective method of computing crop reference evaporation was determined and applied as early as 1988 (Van Zyl & De Jager, 1987; De Jager & Van Zyl, 1989).

Given the overall decision support and problem solving objective with respect to saving water (irrigation scheduling and planning) and climate impacts (on yield forecasting, assessing production potential and drought monitoring); the modelling approach centred on refining model accuracy, specifically with respect to crop phenology, crop water use and crop yield. The overriding impact of climate requires reliable weather data. Research therefore emphasised the use of data from automatic weather stations, modules for computing crop evaporation, and computerised transfer using rapidly advancing telecommunication technology.

PUTU models have been used for: determining crop water and irrigation requirements (De Jager & Van Zyl, 1989); optimising irrigation water use (De Jager, 1978; Mottram & De Jager, 1994; De Jager, 1997); incorporating weather-based irrigation scheduling advice founded upon research into a participatory management approach (De Jager et *al.,* 1982; De Jager *et al*., 1987; De Jager & Kennedy, 1996); ENSO based drought monitoring (Lourens & De Jager, 1996; De Jager *et al*., 2000) and identifying drought mitigation crop production strategies (Singels & Potgieter, 1996); quantifying production potential and production risk of different wheat and maize production strategies using stochastic dominance (Singels & De Jager, 1991b; De Jager & Singels, 1988); identifying optimal wheat cultivar traits and production practices for different environments (Singels & De Jager, 1991a; 1991b; Singels, 1992); forecasting wheat, maize and grazing yields (these models are currently used by consultants in operational forecasting of crop and rangeland yields (Singels, 1995; Fouché, 1992; Howard, 1997; De Jager *et al.*, 2000; Mottram & De Jager, 1994); characterisation of grassland drought (Booysen, 1983; Fouché *et al.*, 1985; Fouché, 1992; Howard, 1997).

PUTU models have also been widely used in consultation studies to provide quantitative information to private and government agencies on crop production potential and risk, crop water and irrigation requirements and impacts of perched water tables.

The PUTU modelling principles and program structure have formed the core of a modelling course presented to graduate and post-graduate students in Agriculture at the University of the Free State since 1980, thereby making a crucial contribution to building much needed crop modelling capacity and establishing a systems approach to addressing agricultural issues in South Africa and elsewhere.

SAPWAT

SAPWAT (South African Program Water) was developed as a planning and management tool for the estimation of crop irrigation requirements by irrigation engineers, agriculturalists, managers and farmers (Crosby & Crosby, 1999).

The first publication on estimating crop irrigation requirements in SA was a document issued by the Department of Agriculture that as a consequence of its green cover was dubbed the Green Book. A later and far more comprehensive publication “Estimated Irrigation Requirements of Crops in South Africa” (Green, 1985a; 1985b) inherited the name. This was the definitive work at the time and widely used for irrigation planning and management. In using long-term rainfall and evaporation time series together with a daily water balance model to compute irrigation requirements, it assumed that potential (unstressed) crop evapotranspiration (ETp) is directly proportional to the American class A-pan evaporation (Epan), the ratio ETp:Epan being defined as the crop factor (later named crop coefficient).

Subsequent developments in irrigation research and technology offered opportunities to improve the accuracies of ETp estimates. These, exploited as far as possible in SAPWAT, were: accounting for short cycle irrigation methods (information in the Green Book only applied to long cycle flood and sprinkler irrigation); relating ETp to evaporation from a short grass (Eo) – a more realistic proxy for ETp than Epan (Doorenbos & Pruitt, 1977); accounting for the effect of climate, planting date and configuration and cultivar characteristics on the crop coefficient; separating evaporation from soil and vegetation (dual crop coefficient approach as opposed to the single factor approach) (Allen *et al.*, 1998); and computerising data and procedures to promote wide and customised application.

Crosby (1996), in developing SAPWAT1.0, made use of the estimated irrigation requirement for 712 climatic zones as calculated by Dent *et al.* (1988) from Epan data. Epan-applicable crop factors were converted to Eo-applicable crop factors by using a conversion factor of 5/7 derived from the Linacre (1977) equation. In the current SAPWAT version (Crosby & Crosby, 1999), monthly average Eo values were calculated for 350 SA weather stations using the FAO24 (Doorenbos & Pruitt, 1977) and FAO33 (Doorenbos *et al.,* 1979) methodology, instead of deriving Eo from Epan data. Procedures were developed to adjust crop coefficients to account for the effects of ground cover, wetted area, frequency of irrigation, cover crops, perennial crops and different irrigation systems and strategies. These were based on the work by De Jager and Van Zyl (1989) and Stroosnijder (1987). Long-term mean monthly effective rainfall was calculated using the Soil Conservation Service routine (Jensen *et al.,* 1989). Irrigation requirements were derived by subtracting effective rainfall from evapotranspiration.

Climate (temperature and photoperiod in particular) drives crop phenological development and therefore will influence values of crop coefficients. Hence, expressing crop coefficients as a function of time could be problematic when large differences in climate exist. This was addressed by dividing SA into seven agro-climatic regions with default crop coefficients values that reflected the typical crop phenology for each region. These values were based on expert opinion.

Crop yields were calculated using the Doorenbos *et al.* (1979) approach. This allows SAPWAT to be used for evaluating irrigation strategies for given soil/climate/management scenarios in terms of water use efficiency and crop productivity.

SAPWAT has been fully adopted by the DWAF as a tool for determining irrigation water allocations in connection with the registering and licensing of agricultural water use. SAPWAT has also been used by many commercial planners and designers for applications that require estimates of crop irrigation use or requirements for commercial and smallholder irrigated agriculture (e.g. Van Heerden *et al*., 2001). Although SAPWAT is not a real-time scheduling model, it can be used to provide pre-season irrigation programmes based on historic weather data. The SAPWAT registration list shows more than 300 users in 14 countries. The software is easily available and can be downloaded from *www.sapwat.org.za.*

Functionality has also been developed for estimating irrigation requirements of entire crop production systems and for estimating water harvest sizes and storage capacities for home gardens (Van Heerden, 2004). SAPWAT3, which is due for release soon, is completely FAO56 (Allen *et al*, 1998) based and includes the CLIMWAT (Smith, 1993) global weather database as well as 50 years of daily weather data for every quaternary catchment of SA (Schulze & Maharaj, 2006). SAPWAT3 uses the Köppen climate system (Köppen, 1931; Strahler & Stralher 2002) for calculating crop coefficients and will therefore be widely applicable.

SWB

The SWB (Soil Water Balance) model (Annandale *et al.,* 1999a) was developed from NEWSWB, a generic crop model based on a simple water balance model published by Campbell and Diaz (1988). In SWB, daily increment of biomass is simulated as either limited by intercepted radiation (Monteith, 1977) or by water supply (Tanner & Sinclair, 1983). Biomass partitioning to the various plant components is influenced by water stress, which also affects the crop canopy. Crop development depends on thermal time. The soil water balance is simulated following the layered, cascading approach (Annandale *et al.,* 1999a). The model was calibrated (Olivier & Annandale, 1998) and the water balance validated (Annandale *et al.,* 2000) for peas.

Further development and application of the model was dictated by practical needs in irrigated agriculture. Specific crops for which the model has been parameterised, include several winter vegetables (Jovanovic *et al*., 1999), summer vegetables (Jovanovic & Annandale, 2000a), potatoes (Steyn, 1997; Geremew *et al*., 2007), field crops (Jovanovic *et al*., 2000a; 2002b; Annandale *et al*., 2002b; Tesfamariam, 2004) and several pasture crops (Beletse, 2004; Annandale *et al*., 2007). A FAO type crop factor water balance module was also added to SWB as an option (Jovanovic & Annandale, 1999).

Incorporation of the chemical equilibrium routine of Robbins (1991) and a weather generator (Jovanovic *et al*., 2003b) into SWB enabled the simulation of long-term effects of irrigation with mine-water (Annandale *et al*., 1999b). The effects of soil and environmental factors on crop salt tolerance could then be modelled dynamically (Jovanovic & Annandale, 1998), and a user-friendly chemical equilibrium calculator for $CaSO_4$ solutions was developed (Jovanovic *et al*., 2003a). Algorithms were also developed to account for the two-dimensional energy and water balances of fruit trees. A complex solar radiation interception model was developed and tested to account for sun angle, row orientation and spacing, tree size and shape, and leaf area density (Annandale *et al*., 2004). A two dimensional finite difference soil water balance was also added to account for partial soil wetting with micro-irrigation (Annandale *et al*., 2003), and the one dimensional finite difference routine has been useful for estimates of the contribution of shallow water tables to crop water use (Jovanovic *et al*., 2004).

A major focus was to develop a real-time irrigation scheduling aid for farm level management and a user-friendly, versatile version of SWB was released in 1998 (Annandale *et al*., 1999a). This was followed by a technology transfer project (Annandale *et a*l., 2005) to overcome the disappointing adoption of SWB as an irrigation scheduling aid. Consultants and irrigators were asked to suggest improvements to the software and were trained to use it. Such a high-tech approach (requiring access to computers and daily weather data) precluded adoption by resource-poor irrigators. The approach here was to use SWB to generate site-specific irrigation calendars that could be distributed to farmers with the help of extension officers (Annandale *et al*., 2005; Geremew *et al*., 2008). Interest remains limited in using the model for real-time irrigation scheduling.

Examples of other applications of SWB are: determination of economic efficiency and farming risk of different irrigation strategies (Benade *et al*., 2002); feasibility studies of using saline or neutralised acid mine-water for irrigated crops with extensive commercial scale field trials confirming model predictions of the potential for mine water irrigation on well-drained soils (Annandale *et a*l., 2001; Annandale *et al*., 2002c; Jovanovic *et al*., 2002b, Annandale *et al*., 2007); prediction of long-term environmental impacts and sustainability of irrigation with mine water (Annandale *et al*., 2006; Beletse *et al*., 2008); and determination of water requirements of peaches (Du Sautoy *et al*., 2003).

Nutrient management, specifically nitrogen (N) and phosphorus (P), are currently being studied to predict the contribution of agriculture to non-point source pollution (Annandale & Du Preez, 2005), and to efficiently utilise sewage sludges in crop production. N and P cycling routines have been built into SWB, with much attention paid to simulating bio-solid mineralisation rates. It is expected that SWB will be specifically useful in designing best management practices to minimise field scale nutrient losses and develop environmentally responsible guidelines for sewage sludge loading rates.

SWB has also proved to be a very useful teaching aid. It has been used to teach irrigation management (Jovanovic & Annandale, 2000b), and crop physiology (Jovanovic *et al.,* 2000a) to undergraduate students at the University of Pretoria. The ETo error calculator (Annandale *et al.,* 2002a), has been especially useful to illustrate the effects of limited or missing weather data on determination of evapotranspiration. Many postgraduate students have done growth analyses of various crops to parameterise SWB. This has forced them to think quantitatively, and to have a deeper understanding of the behaviour of the system they are dealing with.

Examples of other modelling initiatives

There are other examples of crop model development, testing and application that have taken place outside the major projects. MacRobert and Savage (1998) used a CERES wheat derived model for tactical planning of irrigation, Abraha and Savage (2006) used Cropsyst (Stockle *et al*., 1994) to assess climate change impact on maize yield, and Laurie (1995) tested the COTMOD cotton growth model for SA conditions. Tsubo *et al.* (2005a) developed a simple model of a bean and maize intercrop and applied it (Tsubo *et al.,* 2005) to show that the intercrop makes more efficient use of resources than the sole crops of maize and beans. Venter (1992) developed a model for arid and semi-arid shrubland that was employed operationally to assess droughts in the Karoo (Du Pisani *et al*., 1998).

Analysis of impacts

SA crop and water relations modelling efforts could be assessed by the criteria suggested by Sinclair and Seligman (2000), namely "originality, scientific soundness and the contribution to crop science". We believe that the practical impacts on crop production practices and resource management are also important. The following sections address these issues.

Enhanced scientific understanding

Although much of the modelling in SA was built on existing algorithms and concepts developed internationally, numerous novel concepts were formulated that contributed significantly to a better understanding of crop growth and water use. Considerable emphasis was placed on modelling water relations under rainfed conditions because so much of SA crop production is practised under low rainfall conditions. Examples are refined concepts of (1) soil water availability to the plant (Bennie *et al.,* 1988; Annandale *et al*., 2003), (2) water uptake by the plant (Inman-Bamber, 1995a; Van Antwerpen, 1998; Annandale *et al.,* 2000), (3) evaporation from mixed soil/vegetative surfaces (De Jager *et al*., 1984; De Jager & Van Zyl, 1987; McGlinchey & Inman-Bamber, 1996), and (4) interception of radiation by hedgerow orchards (Annandale *et al*., 2004). Concepts regarding canopy development (Inman-Bamber, 1991, Bezuidenhout *et al*., 2002), biomass accumulation (Inman-Bamber, 1991) and partitioning (Singels & Bezuidenhout, 2002) in sugarcane were original and CANEGRO remains one of the leading sugarcane models in the world. The vernalisation (Singels & De Jager, 1991c) and grain quality (Singels, 1993) sub-models developed for wheat can also be considered as novel at the time.

Strategic impacts

Models have played key roles in strategic investigations such as the assessment of impacts of climate change and land use on crop production and resource sustainability. Examples include: climate change impacts on maize production with CERES-Maize (Du Toit *et al*, 1999) and with ACRU (Schulze & Perks, 2000; Tyson *et al*., 2002); the use of neutralised, gypsum-rich mine water for irrigating crops has been shown to be sustainable, with no long-term detrimental impacts on either soil or groundwater (Annandale *et al*., 2006, Annandale *et al*., 2007); a comparative study with ACRU on water use by sugarcane and natural vegetation, in light of South African legislation on streamflow reduction activities (Schulze *et al*., 1999); and a water use efficiency study with ACRU using assessments of sugarcane yield increments per unit of irrigation water applied for different modes of irrigation (Schulze, 2007a).

SAPWAT has been fully accepted by the DWAF as a strategic planning tool for the budgeting, registration and licensing of agricultural water use in South Africa, while the scientific foundation of DWAF levies on commercial plantation forest water use is ACRU based (Gush *et al*., 2002). It is reassuring to know that the unique and powerful ability of models to dynamically integrate scientific principles and available resource data are used to assist resource policy formulation and execution.

Calibration and testing for local conditions

Most model development in SA has involved adapting existing algorithms and calibrating model parameters for local conditions and cultivars. Examples are (1) accounting for the impacts of wide row spacings (Du Toit *et al*., 1994c), prolificacy (Du Toit & Prinsloo, 2000) and a perched water table (Du Toit *et al*., 2002) on maize growth, and (2) calibration of crop genetic coefficients (Du Toit *et al*., 1994b; Steyn, 1997; Du Toit *et al*., 1998; Jovanovic *et al*., 1999; Annandale *et al*., 1999a; Jovanovic & Annandale, 2000a; Jovanovic *et al*., 2000a; 2000b; Du Sautoy *et al*., 2003; Tesfamariam, 2004).

Another significant activity has been model testing. It is essential to have knowledge about the accuracy of models in simulating the response of crop cultivars to local environmental and management conditions, before the models can be used in research and management applications. All the models reviewed in this paper have undergone thorough and widespread testing of various aspects using observations from local experiments (Inman-Bamber, 1991; Singels & De Jager, 1991; De Vos & Mallet, 1994; Schulze, 1995b; Singels & De Jager 1995; Du Toit *et al*., 1997; Hensley *et al*., 1997; Lumsden *et al.,* 1999, Annandale *et al*., 2000; Singels & Bezuidenhout, 2002; Jovanovic *et al*., 2004; Annandale *et al*., 2007). Phenological development, water balance, biomass and yield simulations, in particular, have received considerable attention. Taking into account application objectives, acceptable simulation accuracies have been achieved in relation to international benchmarks. There seems to be room for improving the simulation accuracy of nutrient relations so that models can be applied with confidence to support nutrient management.

Support for crop production and water management

The most prominent model applications in SA have undoubtedly been in the fields of irrigation management and crop forecasting.

Numerous examples exist of procedures that were developed to provide tactical and operational irrigation advice to various crop industries. The PUTU, SWB, BEWAB and CANESIM models were all first applied for irrigation scheduling support. These models, and ACRU and SAPWAT in particular, have also provided invaluable information for supporting planning and strategic and tactical decision-making in irrigated crop production. It is satisfying to know that much of strategic planning decision making in S.A is based on the sound principles and information from these systems.

In contrast, the scope of adoption of model-based decision support systems (DSS) for irrigation scheduling remains disappointing (Olivier & Singels, 2004; Annandale *et al*., 2005; Van den Berg & Smith, 2005; Stevens, 2006; Pott *et al*., 2008), despite great and persistent efforts by for example the BEWAB, PUTU and SWB groups. This concurs with findings elsewhere in the world (Stephens & Middleton, 2002a). Van den Berg and Smith (2005) have recommended that end users be involved with the development and implementation of DSS to overcome this, while Singels and Smith (2006) demonstrated that hiding the complexity of DSS from end-users could promote adoption.

Models have also contributed to a better understanding of rainfed water relations, especially for crop production systems that rely primarily on soil water stored during fallow periods. Models are able to integrate soil and crop factors with information about past and expected future climate to predict likely productivity levels. This has enabled better tactical decision-making regarding (1) choice of crops or cultivars, planting dates and plant densities, (2) the feasibility of planting of annual crops, and (3) the most appropriate use of resources such as fertiliser and irrigation water.

High seasonal variability in rainfall in rainfed crop production areas in SA poses a challenge for accurate crop forecasts. It provides an obvious opportunity for weather based modelling to suggest ways of improving efficiency of crop production supply chains by quantifying the impact of past and expected future climate on water availability and crop yields. The ACRU sugarcane model, PUTU maize and wheat models, the CERES(SA) maize model and the CANEGRO and CANESIM sugarcane models have all been applied to predict crop yields up to a full growing season in advance. Model code has been used operationally with a national data base of interpolated soil and weather data, to augment conventional forecasts of the SA maize and wheat crops and grassland productivity (Van den Berg, 2008, pers. comm.). SA sugarcane crops have also been forecast operationally by SASRI since 2000 and are valued by the industry. The PUTU grassland model and the shrubland model of Venter (1992) have also been used with great effect to characterise drought conditions in natural vegetation in SA.

Model presentation/packaging

Another area that has received a great deal of attention has been the packaging of model code to improve ease of use, thereby making models available to a wider group of users and enhancing their impact. Examples are: the development of user interface in Pascal initially, and then in Delphi (Borland Software Corp.) for PUTU models; the development of a Delphi interface for the SWB model with extensive use of databases (Annandale *et al*., 1999a); the development of a powerful user interface for the ACRU system (ACRU AAHMS and ACRUview) consisting of suites of programs to aid in the rapid preparation of input data and information; the incorporation of the CANEGRO model into the DSSAT shell ((Inman-Bamber & Kiker, 1997; Jones *et al*., 2007); and the development of web-based user interface for the CANESIM model (Singels & Smith, 2008).

Quality documentation of modelling concepts and user guidelines is important to enable scientific scrutiny and to promote wider and correct use of the model. The ACRU modelling system has a proud record of excellent documentation that is readily available.

Capacity building

Many of the modelling projects in SA have been conducted at universities and hence modelling concepts, applications and software packages have been used to train under- and post-graduate students in crop production, agricultural engineering and hydrology. Examples are the PUTU and BEWAB projects at the UFS, the SWB project at UP and the ACRU project at UKZN. Undergraduate “modelling“ courses are essential in encouraging systems thinking required for understanding the soil-plant-atmosphere system and for effective crop production and natural resource research and management. All tertiary students in agriculture and hydrology should therefore be exposed to basic modelling theory.

Some modelling capacity has also been built through the involvement of post-graduate students in model development and application (for example, over 50 post graduate students have been involved in the development of ACRU). However, the number of prospective crop scientists that have the necessary modelling background and skills to solve problems from a systems perspective, remains too low in SA and many skills have been lost through emigration. Stimulating course work is required at post-graduate level for students that wish to pursue a career in researching crop production and irrigation. Prospective students should be made aware of the benefits of these courses and of the need that exists for skills to address the ever-increasing complexity of challenges facing SA and global agriculture.

It is also important for trained agricultural practitioners and researchers to adopt and effectively utilise new modelling technology in their jobs and this requires marketing and training from modelling teams. The ACRU and DSSAT modelling systems have been presented via numerous courses to many participants locally and abroad. The SWB, PUTU and BEWAB models have also been presented to irrigation consultants and advisors through several courses and workshops. The successful adoption of the SAPWAT by DWAF and by irrigation engineers, consultants and practitioners can be ascribed to good marketing and hands-on training courses.

It can be concluded that crop and resource modelling is an essential part of building agricultural research and management capacity in any country. In South Africa the incorporation of modelling theory and application in some tertiary agricultural and hydrological curricula has a proud history but there is a need to expand this.

Lessons from the past and the way forward

The information presented here reflects a proud history of crop modelling in SA over the past 25 years. The scope and depth of model development and application have been remarkable, as are the impacts on crop science and management of crop production and resource use, especially taking into account the limited manpower and other resources in SA.

It may be worthwhile to investigate factors that contributed to achievements and the converse in crop modelling in SA. The most significant contributions have arisen from projects that had critical mass from a manpower and funding point of view, and were sustained for more than a decade. These projects were all initiated and steered by visionary leaders with excellent scientific reputations and unwavering faith in the technology, often in the face of strong initial scepticism. This leadership was crucial in attracting long term funding (see acknowledgements) required for networking and attracting top students and support staff to build and maintain momentum of projects. In some cases the quality and quantity of these factors (leadership, staff and funding) have declined, which has threatened to nullify progress. This trend must be reversed. In other cases, sound succession planning has paved the way for progress to be sustained into the future.

Strong links with international modelling groups has assisted in building and maintaining modelling capacity in South Africa. Here, the DSSAT network, and several overseas universities, have played a crucial role by accepting SA scientists for courses and research visits overseas, and by presenting modelling workshops in SA. This allowed SA modellers to build on the advances made internationally to rapidly test and refine international models for local conditions and then to apply these with good effect. A strengthening of these links will enhance modelling in SA. Similarly, giving modelling courses to international modelling groups has benefited SA modelling initiatives.

Some SA models are at the cutting edge with respect to the simulation of water relations and crop yield, both from a conceptual and accuracy point of view. This can be ascribed to (1) local expertise in crop water relations and local agronomy and (2) the availability of good quality experimental data. SA can also be regarded as the world leader in the application of modelling and managing water for agriculture and in forecasting crop yields. However, adoption of model-based operational decision support (for example for irrigation scheduling) has been disappointing, as elsewhere in the world.

Model application, and hence its impact, has often been limited by a scarcity of quality resource input data. Although there has been a rapid expansion of the SA weather station network in the past decade with the advent of electronic weather stations, large gaps remain, especially with respect to solar radiation and rainfall.

Research is underway to spatially estimate SA solar radiation (Myburgh, ARC-Institute of Soil Climate and Water, pers. comm.) from satellite imagery, similar to the work by Bois *et al.* (2008). Near-real time rainfall maps can be produced by using remote sensing technology (Deyzel *et al.*, 2004; Pegram *et al.*, 2006). In regard to historical data, excellent 50 year databases have recently been created for daily values of temperature, solar radiation and potential evapotranspiration at a spatial resolution of one arc minute, i.e. at ~ 1.7 x 1.7 km intervals (Schulze & Maharaj, 2004; Schulze, 2007a) and for rainfall for each of the 5838 Quirary Catchments covering SA (Lynch, 2004; Warburton & Schulze, 2005).

Detailed soil and land use data have also been difficult to obtain and this has often limited the application of models. However, the ACRU system is linked to a large database of soil and landcover for 1946 Quaternary Catchments in SA, Lesotho and Swaziland, as well as 5838 Quinary Catchments. This database is now available on DVD from the new "South African Atlas of Climatology and Agrohydrology" (Schulze, 2007a) and is also utilised by SAPWAT and SWB. Current remote sensing technology offers realistic opportunities for obtaining up to date, high resolution land use data (area under crops, crop cover, planting and harvesting dates) and possibly soil input data.

Satellite imagery has also been used elsewhere to reset model simulations with measured data for crop cover and growth status (e.g. Doraiswamya *et al.*, 2005; Jongschaap, 2006). Crop production and resource management in SA could benefit greatly if this technology is combined with modelling.

Worldwide there is great interest in using crop models to assist in defining ideotypes for specific environment/management situations. The advent of genomics provides a great opportunity to incorporate genetic information at the gene level with mathematical models that predict the response of genes to environmental factors (Yin *et al.*, 2004, Hoogenboom *et al.*, 2004; Hammer *et al.*, 2006). International developments in this regard should be followed closely and this potentially powerful application of crop models exploited through both international collaboration and local research programmes.

SA does not have the skilled manpower to independently maintain crop modelling systems at the level necessary for maintaining and advancing the efficiency and sustainability of SA crop production in an increasingly complex and competitive environment. SA research groups need to collaborate effectively among themselves and with international groups, so that advances made elsewhere can be exploited. The modular approach followed by leading modelling groups such as APSIM (Keating *et al.,* 2003). DSSAT (Jones *et al.*, 2003) and ACRU, and the open approach to intellectual property (code and concepts) encourages collaboration and will allow more rapid progress.

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