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The DSSAT cropping system model☆

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Abstract

The decision support system for agrotechnology transfer (DSSAT) has been in use for the last 15 years by researchers worldwide. This package incorporates models of 16 different crops with software that facilitates the evaluation and application of the crop models for different purposes. Over the last few years, it has become increasingly difficult to maintain the DSSAT crop models, partly due to fact that there were different sets of computer code for different crops with little attention to software design at the level of crop models themselves. Thus, the DSSAT crop models have been re-designed and programmed to facilitate more efficient incorporation of new scientific advances, applications, documentation and maintenance. The basis for the new DSSAT cropping system model (CSM) design is a modular structure in which components separate along scientific discipline lines and are structured to allow easy replacement or addition of modules. It has one Soil module, a Crop Template module which can simulate different crops by defining species input files, an interface to add individual crop models if they have the same design and interface, a Weather module, and a module for dealing with competition for light and water among the soil, plants, and atmosphere. It is also designed for incorporation into various application packages, ranging from those that help researchers adapt and test the CSM to those that operate the DSSAT–CSM to simulate production over time and space for different purposes. In this paper, we describe this new DSSAT–CSM design as well as approaches used to model the primary scientific components (soil, crop, weather, and management). In addition, the paper describes data requirements and methods used for model evaluation. We provide an overview of the hundreds of published studies in which the DSSAT crop models have been used for various applications. The benefits of the new, re-designed DSSAT–CSM will provide considerable opportunities to its developers and others in the scientific community for greater cooperation in interdisciplinary research and in the application of knowledge to solve problems at field, farm, and higher levels.
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1. Introduction

Information needs for agricultural decision making at all levels are increasing rapidly due to increased demands for agricultural products and increased pressures on land, water, and other natural resources. The generation of new data through traditional agronomic research methods and its publication are not sufficient to meet these increasing needs. Traditional agronomic experiments are conducted at particular points in time and space, making results site- and season-specific, time consuming and expensive. Unless new data and research findings are put into formats that are relevant and easily accessible, they may not be used effectively. 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; Tsuji, 1998; Uehara, 1998; Jones et al., 1998), to facilitate the application of crop models in a systems approach to agronomic research. 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 (IBSNAT, 1993; Uehara and Tsuji, 1998). The systems approach provided a framework in which research is conducted to *understand* how the system and its components function. This understanding is then integrated into models that allow one to *predict* the behavior of the system for given conditions. After one is confident that the models simulate the real world adequately, computer experiments can be performed hundreds or even thousands of times for given environments to determine how to best *manage* or *control* the system. DSSAT was developed to operationalize this approach and make it available for global applications. The DSSAT helps decision-makers by reducing the time and human resources required for analyzing complex alternative decisions (Tsuji et al., 1998). It also provides a framework for scientific cooperation through research to integrate new knowledge and apply it to research questions.

Prior to the development of the DSSAT, crop models were available, but these were used mostly in labs where they were created. For example, the original crop models implemented in DSSAT, the CERES models for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985) and the SOYGRO soybean (Wilkerson et al., 1983) and PNUTGRO peanut (Boote et al., 1986) models, were already enjoying early successes. Those models required different file and data structures and had different modes of operation. Because the IBSNAT project aimed to provide a framework for cropping system analysis, these crop models had to be revised to make them compatible regarding data inputs and application modes. The decision to make these models compatible led to the design of the DSSAT and the ultimate development of compatible models for additional crops, such as potato, rice, dry beans, sunflower, and sugarcane (Hoogenboom et al., 1994a; Jones et al., 1998; Hoogenboom et al., 1999). In DSSAT v3.5, the latest release at the time this paper was written, there are models for 16 different crops and a bare fallow simulation.

The DSSAT is a collection of independent programs that operate together; crop simulation models are at its center (Fig. 1). Databases describe weather, soil, experiment conditions and measurements, and genotype information for applying the models to different situations. Software helps users prepare these databases and compare simulated results with observations to give them confidence in the models or to determine if modifications are needed to improve accuracy (Uehara, 1989; Jones et al., 1998). In addition, programs contained in DSSAT allow users to simulate options for crop management over a number of years to assess the risks associated with each option. DSSAT was first released (v2.1) in 1989; additional releases were made in 1994 (v3.0) (Tsuji et al., 1994) and 1998 (v3.5) (Hoogenboom et al., 1999).

The DSSAT is currently undergoing major revisions, not in its aim but in its design. One major reason for this re-design is that each individual crop model in DSSAT v3.5 had its own soil model components. Although simulation of crop rotations was possible in that version, the

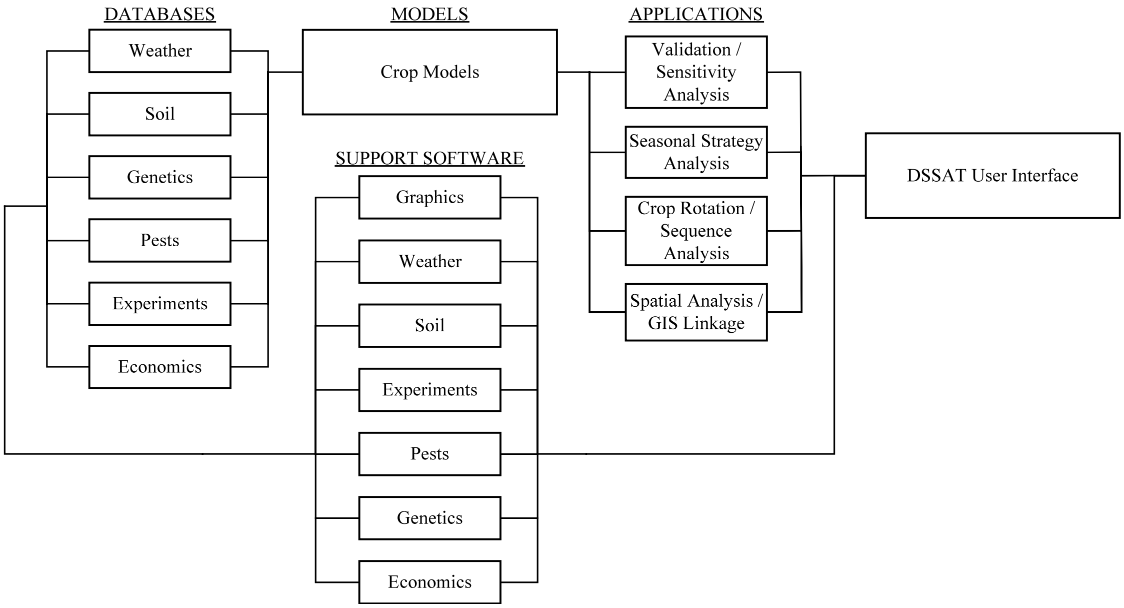

Fig. 1. Diagram of database, application, and support software components and their use with crop models for applications in DSSAT v3.5.

approach that was used was fraught with many problems regarding programming, compatibility of soil models, and potential bugs in different sets of code. At the heart of the DSSAT revisions is a new cropping system model (DSSAT–CSM), which incorporates all crops as modules using a single soil model. This was accomplished by completely redesigning the crop models, starting with CROPGRO, using a modular structure (Jones et al., 2001). This design was motivated to a large extent by the modular features of APSIM (McCown et al., 1996), but it uses the approach developed by van Kraalingen (1990, 1991, 1995), Kraalingen et al. (2003) in the FSE/FST software for programming the behavior of each module. The new CSM now contains models of 16 crops derived from the old DSSAT CROPGRO and CERES models (maize, wheat, soybean, peanut, rice, potato, tomato, drybean, sorghum, millet, pasture, chickpea, cowpea, velvetbean, brachiaria grass, and faba bean).

The aims of the DSSAT–CSM are (1) to simulate monocrop production systems considering weather, genetics, soil water, soil carbon and nitrogen, and management in single or multiple seasons and in crop rotations at any location where minimum inputs are provided, (2) to provide a platform for easily incorporating modules for other abiotic and biotic factors, such as soil phosphorus and plant diseases, (3) to provide a platform that allows one to easily compare alternative modules for specific components to facilitate model improvement, evolution, and documentation, and (4) to provide a capability for easily introducing the CSM into additional application programs in a modular, well documented way. The purpose of this paper is to describe the DSSAT–CSM, its design, data requirements, evaluation and applications.

2. Overall description of the DSSAT cropping system model

The DSSAT–CSM simulates growth, development and yield of a crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time. The DSSAT–CSM is structured using the modular approach described by Jones et al. (2001) and Porter et al. (2000). The most important features of our approach are:

- It separates modules along disciplinary lines,
- It defines clear and simple interfaces for each module,
- It enables individual components to be plugged in or unplugged with little impact on the main program or other modules, i.e. for comparison of different models or model components,
- It facilitates documentation and maintenance of code,
- It enables modules written in different programming languages to be linked together,
- It allows for easy integration into different types of application packages due to the well defined and documented interface to the modules,
- It allows for evolution to integrate other components, such as livestock and intercropping, through well defined module interfaces, and
- It facilitates cooperation among different model development groups where each can focus on specific modules as building blocks for expanding the scope and utility of the CSM. All coauthors of this paper actively contributed to the overall design of DSSAT–CSM, provided modules, and are responsible for maintenance of specific modules.

The DSSAT–CSM has a main driver program, a land unit module, and modules for the primary components that make up a land unit in a cropping system (Fig. 2). The Primary modules are for weather, soil, plant, soil–plant–atmosphere interface, and management components. Collectively, these components describe the time changes in the soil and plants that occur on a single land unit in response to weather and management. In contrast to earlier versions of DSSAT and its crop models, the DSSAT–CSM incorporates models of all crops within one set of code allowing all crops to utilize the same soil model components. This design feature greatly simplifies the simulation of crop rotations since soil processes operate continuously, and different crops are planted, managed, and harvested according to cropping system information provided as inputs to the model.

Each module has six operational steps, as shown in Fig. 2 (run initialization, season initialization, rate calculations, integration, daily output, and summary output). The main program controls when each of these steps is active, and when each module performs the task that is called for. This feature, an adaptation of van Kraalingen's (1991, 1995) work, allows each module to read its own inputs, initialize itself, compute rates, integrate its own state variables, and write outputs completely independent from the operation of other modules. Only a few 'interface' variables are communicated to and from each module. This allows one to 'unplug' a module and replace it with a different one as long as it communicates the same variables to the rest of the modules, even if the parameters, state variables, and module input files are different. State variables are written after integration to represent the state of the system at the end of the day, and initial values are written during initialization for day 0. More details of this modular design can be found in Porter et al. (2000).

Different types of applications are accomplished in DSSAT–CSM by using different modes to call the land unit module on a daily basis; the mode is specified as a command line argument when the model is run. The basic mode provides for interactive sensitivity analysis and comparison of simulated vs. observed field data. A second mode of operation simulates crops over a number of years of weather using the same soil initial conditions. This mode allows one to evaluate the effects of uncertain future weather conditions on decisions made when all soil initial conditions are known. A third mode operates the cropping system modules to simulate crop rotations over a number of years, and soil conditions are initialized only at the very start of the simulation. A fourth mode operates the CSM to simulate one or more crops over space (i.e. for precision agriculture, land use management or other spatial-based applications). One can also completely replace the main driver for other applications, thereby providing a highly flexible approach for development of additional applications and user interfaces

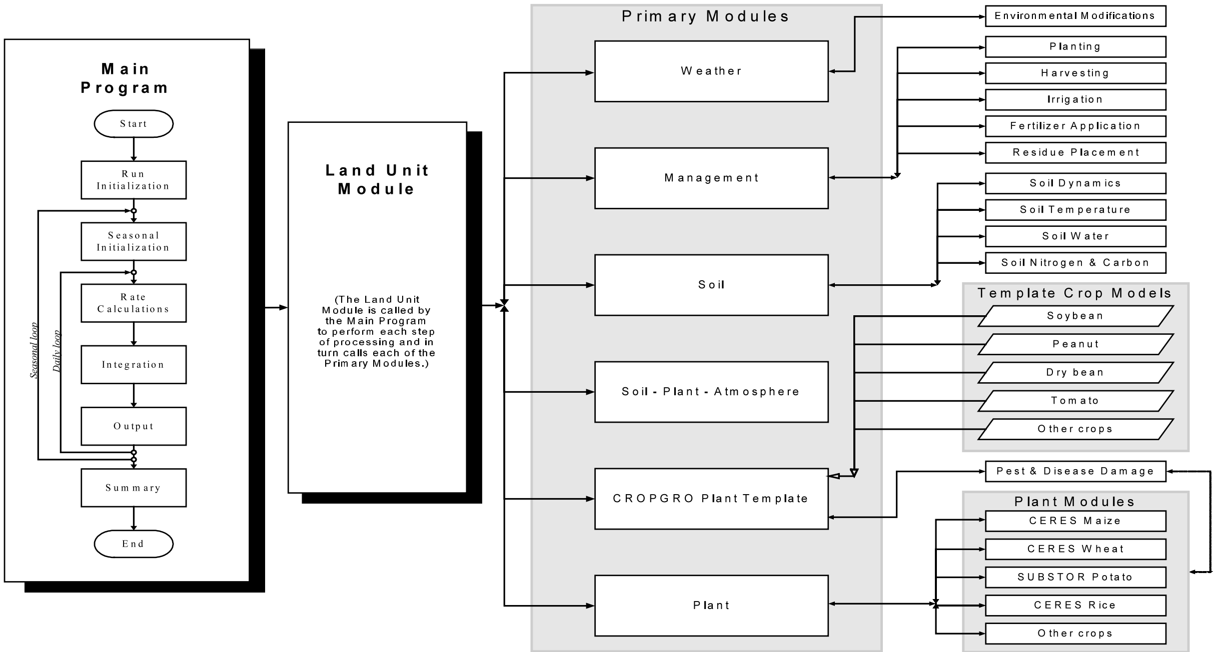

Fig. 2. Overview of the components and modular structure of the DSSAT–CSM.

without having to modify code for any other module. The application driver communicates with only one module—the Land Unit module as shown in Fig. 2. The Land Unit Module provides the interface between the application driver (main program) and all of the components that interact in a uniform area of land.

Table 1 lists the primary and sub modules currently used in the CSM and summarizes their functions. There are two important points to be made about this table. First, sub modules operate exactly like Primary modules. Each sub module will usually perform six steps, and thus it can be replaced by another module that can operate with its defined input interface variables and produce the defined module output interface variables. Thus, the concept of 'interface' variables is critical to the modular approach used in DSSAT–CSM. There can be additional levels of sub modules, each behaving the same way. For example, the CERES-Maize sub module could have a phenology sub module. One could unplug this phenology module, for example, and introduce a new one, if desired, without changing the rest of the CERES-Maize module. Any module or sub module can also have other subroutines as needed; there are no technical restrictions about how simple or complex a module should be.

The second important point is that there are two different ways of introducing new crops into the DSSAT–CSM. One can introduce a new module for a crop by interfacing it with the Plant module. This is the approach that was used to interface the CERES and other models, which were operated as stand-alone crop models in DSSAT v3.5, such as potato, cassava, sugarcane, and sunflower. In this approach, a model developer would create the code for the crop growth module, adhering to the interface for the Plant module described below, and simply add it to the rest of the code. An advantage of this approach is that it enables one to easily test a model from outside the DSSAT group. The second way to introduce a new crop is through the use of a Crop Template approach. This can be implemented with the CROPGRO approach and allows users to modify values in a species Crop Template file without changing any code. The CROPGRO development team has used this approach in creating models for different species, including faba bean (Boote et al., 2002),

Table 1
Summary description of modules in the DSSAT–CSM

Modules	Sub modules	Behavior
Main program (DSSAT–CSM)		Controls time loops,, determines which modules to call based on user input switches, controls print timing for all modules
Land unit		Provides a single interface between cropping system behavior and applications that control the use of the cropping system. It serves as a collection point for all components that interact on a homogenous area of land
Weather		Reads or generates daily weather parameters used by the model. Adjusts daily values if required, and computes hourly values
Soil	Soil dynamics	Computes soil structure characteristics by layer. This module currently reads values from a file, but future versions can modify soil properties in response to tillage, etc
	Soil temperature module	Computes soil temperature by layer
	Soil water module	Computes soil water processes including snow accumulation and melt, runoff, infiltration, saturated flow and water table depth. Volumetric soil water content is updated daily for all soil layers. Tipping bucket approach is used
	Soil nitrogen and carbon module	Computes soil nitrogen and carbon processes, including organic and inorganic fertilizer and residue placement, decomposition rates, nutrient fluxes between various pools and soil layers. Soil nitrate and ammonium concentrations are updated on a daily basis for each layer
SPAM		Resolves competition for resources in soil–plant–atmosphere system. Current version computes partitioning of energy and resolves energy balance processes for soil evaporation, transpiration, and root water extraction
CROPGRO Crop Template module		Computes crop growth processes including phenology, photosynthesis, plant nitrogen and carbon demand, growth partitioning, and pest and disease damage for crops modeled using the CROPGRO model Crop Template (soybean, peanut, dry bean, chickpea, cowpea, faba bean, tomato, Macuna, Brachiaria, Bahiagrass)
Individual plant growth modules	CERES-Maize; CERES-Wheat; CERES-Rice; SubStor-Potato; Other plant models	Modules that simulate growth and yield for individual species. Each is a separate module that simulates phenology, daily growth and partitioning, plant nitrogen and carbon demands, senescence of plant material, etc
Management operations module	Planting	Determines planting date based on read-in value or simulated using an input planting window and soil, weather conditions
	Harvesting	Determines harvest date, based on maturity, read-in value or on a harvesting window along with soil, weather conditions
	Irrigation	Determines daily irrigation, based on read-in values or automatic applications based on soil water depletion
	Fertilizer	Determines fertilizer additions, based on read-in values or automatic conditions
	Residue	Application of residues and other organic material (plant, animal) as read-in values or simulated in crop rotations

brachiaria grass (Giraldo et al., 1998), tomato (Scholberg et al., 1997), chickpea (Singh and Virmani, 1994) and velvet bean (Hartkamp et al., 2002), for example. A major advantage of this approach is that working with the Crop Template will no doubt be less prone to errors.

3. Component descriptions

The main program reads information from the DSSAT standard file that describes a particular experiment or situation to be simulated (Hunt et al., 2001) and sets a number of variables for controlling a simulation run. It initiates the simulation by setting the DYNAMIC variable for initializing the run and calls the Land Unit module. It then starts a crop season time loop and calls the Land Unit module for initializing variables that must be set at the start of each season. After initialization of the seasonal loop, the main program starts a daily loop and calls the Land Unit module three times in sequence, first to compute rates, secondly to integrate, and finally to report daily outputs. After a crop season is completed, it calls the Land Unit module to produce season-end variables and to create summary output files. A summary of these operations is presented in Fig. 2. The main program provides these timing and simulation control variables to all modules.

The Land Unit module calls each of the primary cropping system modules shown in Fig. 2 each day. At the start of each new crop season, it obtains management information from the DSSAT input file. The Land Unit and Primary modules link to sub modules, and thus are used to aggregate processes and information describing successive components of the cropping system. For example, the Soil module has four sub modules that integrate soil water, soil carbon and nitrogen, soil temperature and soil dynamics processes. The Plant module has sub modules for various crops. Below, we describe these modules and sub modules, emphasizing those for simulating soil and plant growth processes and their interactions. Table 2 shows the variables that are currently passed from each of the Primary modules to the Land Unit module, excluding the timing and control variables. These interface variables are available for any primary module since they are passed into the Land Unit module.

3.1. Weather module

The main function of the Weather module is to read or generate daily weather data. It reads in daily weather values (maximum and minimum air temperatures, solar radiation and precipitation, relative humidity and wind speed when available), from the daily weather file. Hourly weather values are computed for use by some modules that require them. This module generates daily weather data using the WGEN (Richardson, 1981, 1985) or SIMMETEO (Geng et al., 1986, 1988) weather generators. It also can modify daily weather variables for studying climate change or simulating experiments in which solar radiation, rainfall, maximum and minimum temperatures, day length, and/or atmospheric CO_2 concentrations were set at constant values or increased/decreased relative to their read-in values. Based on the inputs provided from the management file, the Weather module knows whether to just read-in daily values or to generate or modify them (using the Environmental Modification sub module). The variables listed in Table 2a are passed through its interface.

3.2. Soil module

The soil in the land unit is represented as a one-dimensional profile; it is homogenous horizontally and consists of a number of vertical soil layers. The Soil module integrates information from four sub modules: soil water, soil temperature, soil carbon and nitrogen, and soil dynamics. Table 2b defines the variables produced by this module for use in other modules. The soil dynamics module is designed to read-in soil parameters for the land unit and to modify them based on tillage, long-term changes in soil carbon, or other field operations. The soil dynamics module currently reads in soil properties from a file. Descriptions of the other three sub modules of Soil are given below.

Table 2
Definition of all interface variables showing the primary modules in which they are computed and provided as outputs in the current version of DSSAT–CSM

Variable	Definition	Variable	Definition
(a) Weather module (WEATHR) outputs			
CLOUDS	Relative cloudiness factor (0–1)	TAV	Average annual air temperature (°C) (used with TAMP to calculate soil temperature)
CO_2	Atmospheric carbon dioxide concentration (μmol[CO_2]/mol[air])	TDEW	Dew point temperature (°C)
DAYL	Day length on day of simulation (from sunrise to sunset) (h)	TGRO(I)	Hourly air temperature (°C)
PAR	Daily photosynthetically active radiation or photon flux density (moles[quanta]/(m^2 d))	TMAX	Maximum daily temperature (°C)
RAIN	Daily total precipitation (mm)	TMIN	Minimum daily temperature (°C)
SRAD	Daily total solar radiation (MJ/(m^2 d))	WINDSP	Wind speed (km/d)
TAMP	Amplitude of annual air temperature (°C) (used to calculate soil temperature)	XLAT	Latitude (°)
(b) Soil module (SOIL) outputs			
BD(L)	Bulk density, soil layer L (g[soil]/cm^3[soil])	PH(L)	pH in soil layer L
DLAYR(L)	Thickness of soil layer L (cm)	SAT(L)	Soil water content in layer L at saturation (cm^3[water]/cm^3[soil])
DUL(L)	Soil water content at drained upper limit in soil layer L (cm^3[water]/cm^3[soil])	SRFTEMP	Temperature of soil surface litter (°C)
LL(L)	Soil water content in soil layer L at lower limit of plant extractable soil water (cm^3[water]/cm^3[soil])	ST(L)	Soil temperature in soil layer L (°C)
NH_4(L)	Ammonium N in soil layer L (μg[N]/g[soil])	SW(L)	Soil water content in layer L (cm^3[water]/cm^3[soil])
NLAYR	Actual number of soil layers	SWDELTS (L)	Change in soil water content due to drainage in layer L (cm^3[water]/cm^3[soil])
NO_3(L)	Nitrate in soil layer L (μg[N]/g[soil])	WINF	Water available for infiltration-rainfall plus net irrigation minus runoff (mm/d)
(c) Plant growth module outputs (from CROPGRO Crop Template and PLANT Modules)			
NSTRES	Nitrogen stress factor (1 = no stress, 0 = max stress)	UNO3(L)	Rate of root uptake of NO_3 (kg[N]/(ha d))
RLV(L)	Root length density for soil layer L (cm[root]/cm^3[soil])	XHLAI	Healthy LAI (m^2[leaf]/m^2[ground])
SENCLN(I, J)	Daily senesced plant matter. I = 0 for surface, 1 for soil; J = 1 for C, 2 for lignin, 3 for N (g[C,N,or lignin]/(m^2 d))	XLAI	LAI (m^2[leaf]/m^2[ground])
STGDOY(I)	Day when plant stage I occurred (YYDDD)(YRDOY)	YREMRG	Day of emergence (YYDDD)
UNH_4(L)	Rate of root uptake of NH_4 (kg[N]/(ha d))	YRNR8	Harvest maturity date (YYDDD)(YRDOY)
(d) SPAM outputs			
EO	Potential ET rate (mm/d)	SWDELTX(L)	Change in soil water content due to root water uptake in layer L (cm^3[water]/cm^3[soil])
EOP	Potential plant transpiration rate (mm/d)	TRWU	Actual daily root water uptake over soil profile (cm/d)
FDINT	Light interception by leaves	TRWUP	Potential daily root water uptake over soil profile (cm/d)
FLOW(L)	Unsaturated soil water flow: + = upward, − = downward (cm/d)		
(e) Operations management module outputs (OPMGMT)			
FERTYPE	Fertilizer type for current application	RESSRF	Residue left on surface of soil (kg[residue]/ha)
FERDEPTH	Fertilizer incorporation depth on current day of simulation (cm)	RESNIT	N concentration of the residue for current application (%)

Table 2 (*Continued*)

Variable	Definition	Variable	Definition
FERNIT	Amount of nitrogen in fertilizer applied on current day of simulation (kg[N]/ha)	RESDEPTH	Incorporation depth of newly added residues (cm)
HAREND	End of season or harvest date (YYDDD)	RESTYPE	Residue type for current application
IRRAMT	Irrigation amount for today (mm/d)	YRPLT	Planting date (YYDDD)
RESSOL	Amount of residue applied to the soil (kg[dry matter]/ha)		

3.2.1. Soil water sub module

The soil water balance model developed for CERES-Wheat by Ritchie and Otter, (1985) was adapted for use by all of the DSSAT v3.5 crop models (Jones and Ritchie, 1991; Jones, 1993; Ritchie, 1998). This one-dimensional model computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, and root water uptake processes. In the new DSSAT–CSM, soil evaporation, plant transpiration, and root water uptake processes were separated out into a soil–plant–atmosphere module (SPAM) to create more flexibility for expanding and maintaining the model. Otherwise, the water balance model in DSSAT–CSM is the same as in DSSAT v3.5 individual crop models, and individual processes are modeled using the same logic and equations. The soil has parameters that describe its surface conditions and layer-by-layer soil water holding and conductivity characteristics (Table 2b). The model uses a 'tipping bucket' approach for computing soil water drainage when a layer's water content is above a drained upper limit parameter. Upward unsaturated flow is also computed using a conservative estimate of the soil water diffusivity and differences in volumetric soil water content of adjacent layers (Ritchie, 1998).

Soil water infiltration during a day is computed by subtracting surface runoff from rainfall that occurs on that day. The SCS method (Soil Conservations Service, 1972) is used to partition rainfall into runoff and infiltration, based on a 'curve number' that attempts to account for texture, slope, and tillage. The modification to this method that was developed by Williams et al. (1984) is used in the model; it accounts for layered soils and soil water content at the time when rainfall occurs. When irrigation is applied, the amount applied is added to the amount of rainfall for the day to compute infiltration and runoff. Drainage of liquid water through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer, if this parameter is provided. If the saturated hydraulic conductivity of any layer is less than computed vertical drainage through that layer, actual drainage is limited to the conductivity value, and water accumulates above that layer. This feature allows the model to simulate poorly drained soils and perched water tables. For example, a soil may have a layer with very low or no drainage at the bottom of the profile. Vertical drainage from the profile would not occur or it would be very low, limited by the saturated hydraulic conductivity value of the bottom layer.

Evaporation of water from the soil surface and root water uptake (transpiration) from each layer are computed in the SPAM and communicated to this soil water balance module. Each day, the soil water content of each layer is updated by adding or subtracting daily flows of water to or from the layer due to each process.

3.2.2. Soil carbon and nitrogen balance sub module

The DSSAT–CSM has two options to simulate the soil organic matter (SOM) and nitrogen balance. The original SOM model in DSSAT v3.5 (Godwin and Jones, 1991; Godwin and Singh, 1998), based on the PAPRAN model of Seligman and Van Keulen (1981), was converted into a modular structure and retained in the new DSSAT–CSM. Additionally, a SOM module developed by Gijsman et al. (2002), based on the

CENTURY model (Parton et al., 1988, 1994), is included. This CENTURY-based module was added to facilitate simulation of soil organic sequestration potential for different crop rotations over long time periods after initializing soil C and other variables only once at the start of the simulation. The main differences are that the CENTURY-based module (i) divides the SOM in more fractions, each of which has a variable C:N ratio and can mineralize or immobilize nutrients, (ii) it has a residue layer on top of the soil, and (iii) the decomposition rate is texture dependent. In both SOM modules, organic matter decomposition depends on soil temperature and water content. Because of the widespread use of the CENTURY model and interest in its use in CSMs, we focus on this component in this section. This version is more appropriate for use in low input agricultural systems, for example those that use green manure where the surface layer is crucial. Gijsman et al. (2002) showed that this new component greatly improved the accuracy of simulating the long-term changes in soil carbon in the Rothamsted bare fallow experiment.

The CENTURY-based module distinguishes three types of SOM: (1) easily decomposable (microbial) SOM1, (2) recalcitrant SOM2, which contains lignin and cell walls, and (3) an almost inert SOM3. At initialization of the simulation, the fractional ratio of these three pools is set, with SOM1 of only about 2% of total SOM, while SOM2 and SOM3 vary with the management history of the soil (grassland or cultivated) and the degree of depletion. The improved SOM module also allows one to perform more realistic simulations on carbon sequestration, i.e. the build up of soil organic C under different management systems.

Most of the interface input variables to the soil carbon and nitrogen balance modules are soil properties and variables computed in the soil water and soil temperature sub modules. Transport of N through the soil to deeper layers is based on water flux values obtained from the soil water module. The only interface variable from the Plant module is the array of plant mass being senesced and abscised onto the soil surface daily. The output variables sent to other modules are ammonium and nitrate nitrogen in each soil layer (Table 2b).

3.2.3. Soil temperature sub module

The soil temperature model currently in the DSSAT–CSM was originally derived from the EPIC model (Williams et al., 1984; Jones et al., 1991) and is the same as the one in the CERES and CROPGRO models in DSSAT v3.5. Soil temperature is computed from air temperature and a deep soil temperature boundary condition that is calculated from the average annual air temperature and the amplitude of monthly mean temperatures. It also includes a simple approach to calculate the impact of solar radiation and albedo on the soil surface temperature. However, it does not consider differences in soil wetness or surface conditions. Soil temperature is used to modify plant processes (emergence) and SOM decomposition. Additional details on this component are in Jones and Kiniry (1986) in the description of the CERES-Maize model.

3.3. Soil–plant–atmosphere module

This module computes daily soil evaporation and plant transpiration. The current version was originally developed by Ritchie (1972) and was used in all of the DSSAT v3.5 crop models as part of the soil water balance. This module brings together soil, plant and atmosphere inputs and computes light interception by the canopy, potential evapotranspiration (ET) as well as actual soil evaporation and plant transpiration (Table 2d). It also computes the root water uptake of each soil layer. The daily weather values as well as all soil properties and current soil water content, by layer, are required as input. In addition, leaf area index (LAI) and root length density for each layer are needed.

The module first computes daily net solar radiation, taking into account the combined soil and plant canopy albedo. It calculates potential ET using one of two current options. The default Priestley and Taylor (1972) method requires only daily solar radiation and temperature, and was described in detail by Ritchie (1972), Ritchie and Otter, (1985) and Jones and Ritchie (1991). The

Penman-FAO (Doorenbos and Pruitt, 1977) method for computing potential ET can optionally be used to better account for arid or windy conditions, but weather data files must include wind and humidity data. We have also created options for using the Penman–Monteith (Monteith, 1986) method for daily potential ET calculations and for using hourly energy balance (unpublished).

The potential ET is partitioned into potential soil evaporation based on the fraction of solar energy reaching the soil surface, based on a negative exponential function of LAI, and potential plant transpiration. Actual soil evaporation is based on a two-stage process (Ritchie, 1972). After the soil surface is first wetted due to either rainfall or irrigation, evaporation occurs at the potential rate until a cumulative soil evaporation amount since wetting is reached. Then, a soil-limiting daily soil evaporation amount is computed as a square root function of time since stage one ended. Actual soil evaporation is the minimum of the potential and soil-limiting calculations on a daily basis. If evaporation is less than potential soil evaporation, this difference is added back to potential plant transpiration to account for the increased heat load on the canopy when the soil surface is dry (Ritchie, 1972).

To determine whether the soil or atmosphere limits plant transpiration, potential root water uptake is computed by calculating a maximum water flow to roots in each layer and summing these values (Ritchie and Otter, 1985; Ritchie, 1998; Jones and Ritchie, 1991). These calculations account for root length density in each layer and the soil water content in the layer. The equation that computes potential root water uptake in each layer is an approximation to the radial flow equation, where assumptions are made about soil texture effect on hydraulic conductivity, root diameter, and a maximum water potential difference between roots and the soil. The actual plant transpiration is then computed as the minimum of potential plant transpiration and the potential root water uptake. Thus, the atmosphere can limit transpiration by low solar radiation and cool temperatures, the canopy can limit it by low LAI, and the soil can limit it by low soil water content, low root length density, and their distributions relative to each other.

This method for computing ET has provided an excellent functional approach for determining water stress in the plant without explicitly modeling water status in the plant component. The ratio of actual ET to potential ET, if less than 1.0, indicates that stomatal conductance would have had to be decreased sometimes during the day to prevent plant desiccation. This ratio is typically used in the Plant modules to reduce photosynthesis in proportion to relative decreases in transpiration. Similarly, a ratio of potential root water uptake and potential transpiration is used to reduce plant turgor and expansive growth of crops. The rationale for this is that as soil water becomes more limiting, turgor pressure in leaves would decrease and affect leaf expansion before photosynthesis is reduced. In the current Plant modules this ratio is set to 1.5.

3.4. Template crop module (CROPGRO)

The CROPGRO Crop Template module in DSSAT–CSM is the same as that described by Boote et al. (1998a), although its components were modified to fit the modular structure. The interface variables linking this module (and the Plant module where CERES and other individual crops are modeled) to other modules are defined in Table 2c. CROPGRO was created after our earlier experience in adapting SOYGRO to PNUTGRO and BEANGRO (Hoogenboom et al., 1994b) suggested to us the value of having one common program with values from files providing information for each species to be modeled. CROPGRO was then developed as a generic approach for modeling crops in the sense that it has one common source code, yet it can predict the growth of a number of different crops. Currently, it simulates ten crops; including seven grain legumes (soybean (*Glycine max* L. Merr.); peanut (*Arachis hypogaea* L.); dry bean (*Phaseolus vulgaris* L.); chickpea; cowpea; velvet bean and faba bean (*Vicia faba* L.)), and non-legumes such as tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997; Boote et al., 1998a,b). This versatility is

Table 3
Summary of types of parameters used in the Crop Template approach

Section	Description
Photosynthesis	Coefficients for partitioning at emergence and final growth stage, stem senescence during water stress, and nodule growth Functions that define leaf N and temperature effects on photosynthesis
Respiration	Respiration parameters associated with various growth processes 'Maximum', 'normal growth', and 'final' protein concentrations of leaf, stem, root, shell, seed, and nodule tissues
Plant composition values	Carbohydrate–cellulose, lipid, lignin, organic acid concentration of leaf, stem, root, shell, seed, and nodule tissues Effects of temperature on seed lipid concentration
Carbon and nitrogen mining parameters	Coefficients for carbohydrate reserves in stem tissue Fraction of new leaf, stem, root and shell tissue growth that is available carbohydrate Mobilization rates of carbohydrate and protein from vegetative tissue
Nitrogen fixation parameters	Nodule growth and senescence parameters Arrays that define the effects of temperature, soil water, and nodule age on nitrogen fixation and nodule growth
Plant growth and partitioning parameters	Dry matter partitioning to leaf, stem, and root as function of vegetative stage Coefficients for partitioning at emergence, final growth stage, stem senescence, during water stress, and nodule growth Parameters that define leaf expansion response to temperature and solar radiation Initial root depth and length, root water uptake parameters Relative effects of temperature on pod set, seed growth and relative change in partitioning Relative effects of soil water content on peanut pegging and pod addition
Senescence factors	Senescence parameters related to vegetative stage, freeze damage, nitrogen mobilization, drought, canopy self shading
Phenology parameters	Curves that define temperature effect on vegetative, early reproductive, and late reproductive development Parameters for each growth stage: preceding stage, photoperiod function, temperature function, temperature and water sensitivity, N & P sensitivity
Canopy height and width growth parameters	Internode length and canopy width increase as a function of plant vegetative stage Internode elongation as a function of temperature and photosynthetic photon flux density

These parameters are contained in a separate species file for each crop using the Crop Template approach of the DSSAT–CSM

achieved through input files that define species traits.

An overview of the types of parameters contained in the species file is given in Table 3. Each species file contains information on base temperatures (T_b) and optimum temperatures (T_{opt}) for developmental processes (rate of emergence, rate of leaf appearance, and rate of progress toward flowering and maturity) and growth processes (photosynthesis, nodule growth, N_2-fixation, leaf expansion, pod addition, seed growth, N mobilization, etc.). The file also includes information on photosynthesis, N_2-fixation, tissue composition, growth and maintenance respiration coefficients.

The CROPGRO Crop Template provides for ecotype and cultivar traits to be defined in read-in files. Table 4 lists cultivar coefficients and definitions (Boote et al., 1998a). Cultivar differences are created by 15 'cultivar' traits. The cultivar traits include two daylength sensitivity traits, five im-

Table 4
Genetic coefficients used in the CROPGRO Crop Template module for modeling different cultivars

Trait	Definition of trait
ECO#	Code for the ecotype to which this cultivar belongs (see *.eco file)
CSDL	Critical short day length below which reproductive development progresses with no daylength effect (for short day plants) (h)
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short day plants) (1/h)
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)
FL-SH	Time between first flower and first pod (R3) (photothermal days)
FL-SD	Time between first flower and first seed (R5) (photothermal days)
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO_2, and high light (mg CO_2/(m^2 s)
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2/g)
SIZELF	Maximum size of full leaf (three leaflets) (cm^2)
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD	Maximum weight per seed (g)
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)
SDPDV	Average seed per pod under standard growing conditions (#[seed]/pod)
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)
Frequently used important traits from the ecotype file	
R1PRO	Increase in daylength sensitivity after anthesis (CSDL decreases by this amount (h))
FL-VS	Time from first flower to last leaf on main stem (photothermal days)
THRESH	The maximum ratio of (seed/(seed+shell)) at maturity causes seed to stop growing as their dry weight increases until shells are filled in a cohort
SDPRO	Fraction protein in seeds (g[protein]/g[seed])
SDLIP	Fraction oil in seeds (g[oil]/g[seed])

Also included are definitions of frequently used traits from the ecotype file.

portant life cycle 'phase' durations, light-saturated leaf photosynthesis, vegetative traits, and reproductive traits. There are 19 traits in the ecotype file that were proposed to vary less often, such as thermal time to emergence and first leaf stages, but some traits from this file have been used frequently to characterize cultivars.

Phenology is an important component of the CROPGRO Crop Template approach. This component uses information from the species file, which contains cardinal temperature values, as well as information from the cultivar and ecotype files, which contain physiological day durations for respective life cycle phases. Life cycle progress through any given phase depends on a physiological day accumulator as a function of temperature and day length, in many cases. Crops like soybean are sensitive to day length, whereas other crops such as peanut are not. When the physiological day accumulator reaches a value defined by a threshold given in the cultivar file, a new growth stage is triggered. A physiological day can be thought of as equivalent to one calendar day if temperatures are optimum 24 h per day and day length is below the critical short or long day length requirement, depending on species sensitivity. The species file also contains coefficients that indicate the effect of water or nitrogen deficit on rate of life cycle progress. These coefficients may vary with life cycle phase; for example, water deficit may slow the onset of reproductive growth but accelerate reproductive growth after beginning seed fill. The species file also allows different cardinal temperatures for pre-anthesis development compared to post-anthesis reproductive development. For additional information on phenology in CROPGRO see papers by Boote et al. (1998a,b), Grimm et al. (1993, 1994), Piper et al. (1996a,b), Mavromatis et al. (2001).

Crop photosynthesis can be calculated by two options: (1) daily canopy photosynthesis, similar to radiation use efficiency models, or (2) hourly hedgerow light interception and leaf-level photosynthesis. The daily canopy photosynthesis option, modified from the method used in SOYGRO V5.4 (Jones et al., 1989), predicts daily gross photosynthesis as a function of daily irradiance for a full canopy, which is then multiplied by factors 0–1 for light interception, temperature, leaf nitrogen status, and water deficit. There are additional adjustments for CO_2 concentration, specific leaf weight, row spacing, and cultivar. The hourly hedgerow photosynthesis light interception approach is described by Boote and Pickering (1994). On an hourly time step during each day, interception and absorption of direct and diffuse light components are computed based upon canopy height and width, LAI, leaf angle, row direction, latitude, day of year, and time of day (Boote and Pickering, 1994). Photosynthesis of sunlit and shaded leaves is computed hourly using the asymptotic exponential response equation, where quantum efficiency and light-saturated photosynthesis rate variables are dependent on CO2 and temperature (Boote and Pickering, 1994). Hourly canopy photosynthesis on a land area basis is computed from the sum of sunlit and shaded leaf contributions by multiplying sunlit and shaded leaf photosynthetic rates by their respective LAIs. The hourly time loop is handled completely by the subroutine that uses this approach; gross photosynthesis is integrated hourly to provide a daily total value for use by other subroutines in the CROPGRO module.

Growth of new tissues depends on daily available carbohydrate, partitioning to different tissues, and respiration costs of tissue synthesis. During vegetative growth, the model follows a partitioning pattern dependent on vegetative growth stage, but modified by water deficit and nitrogen deficiency. Partitioning coefficients for leaf, stem, and root are defined in the species Crop Template file. Beginning at flowering, cohorts of flowers, pods, and seeds are added daily. These cohorts have an explicit assimilate demand per day depending on genetic potential and temperature. Reproductive tissues have first priority for assimilate over vegetative tissues, up to a maximum reproductive partitioning factor. This factor may be less than 1.0 for indeterminate plants (such as peanut and tomato) and 1.0 for determinate plants, indicating that reproductive tissue eventually can utilize 100% of the assimilate. Leaf area expansion depends on leaf weight growth and specific leaf area, where the latter depends on temperature, light, and water deficit. Leaf expansion during reproductive growth is terminated by decrease of assimilate allocated to leaf growth and by reaching a phase that terminates leaf expansion. During seed fill, nitrogen is mobilized from vegetative tissues. As a result photosynthesis declines and leaf abscission increases. Protein and carbohydrate mobilized from vegetative tissue contribute to seed growth while photosynthesis declines. Growth respiration and conversion efficiency follow the approach of Penning de Vries and van Laar (1982) where the glucose cost for respiration and for condensation are computed as a function of the composition of each tissue. The species file contains the glucose cost to synthesize protein, lipid, lignin, organic acid, cellulose-carbohydrate, and mineral fractions as well as the approximate composition of each tissue. Maintenance respiration depends on temperature as well as gross photosynthesis and total crop mass minus protein and oil in the seed. Maintenance respiration is subtracted from gross daily photosynthesis to give available carbohydrates for new tissue growth. Details on these relationships and sources of data used in their development have been published by various authors (Wilkerson et al., 1983; Boote et al., 1986; Jones et al., 1989; Boote and Pickering, 1994; Boote et al., 1997, 1998a,b, 2002).

3.5. Individual crop module interface (plant module)

The individual crop module interface serves the same function as the CROPGRO Crop Template module in that it has the same interface variables (Table 2), linking plant growth dynamics to the other modules in the DSSAT–CSM. However, it is designed to link modules that describe growth, development and yield for individual crops. This module links in, for example, the CERES models from DSSAT v3.5 after modifications were made to fit the modular structure. We have implemented several of the individual models from DSSAT v3.5

Table 5
Growth stages simulated by the DSSAT CERES-maize, wheat and barley models

Maize	Wheat	Barley
Germination	Germination	Germination
Emergence	Emergence	Emergence
End of juvenile		
Floral induction	Terminal spikelet	Maximum primordia
	End ear growth	End ear growth
75% Silking		
Beginning grain fill	Beginning grain fill	Beginning grain fill
Maturity	Maturity	Maturity
Harvest	Harvest	Harvest

(maize, wheat, sorghum, millet, barley, and rice) as well as potato (Hoogenboom et al., 1999; Ritchie et al., 1998; Singh et al., 1998), and we are converting others. One could add additional crops by adhering to the modular structure and providing the interface variables defined in Table 2. Here, we summarize how crop growth is computed for three crops (maize, wheat, and barley).

Table 6
Genetic coefficients for the DSSAT CERES-Maize, Wheat and Barley models

(A) Maize	
P1	Degree days (base 8 °C) from emergence to end of juvenile phase
P2	Photoperiod sensitivity coefficient (0–1.0)
P5	Degree days (base 8 °C) from silking to physiological maturity
G2	Potential kernel number
G5	Potential kernel growth rate mg/(kernel d)
PHINT	Degree days required for a leaf tip to emerge (phyllochron interval) (°C d)
(B) Wheat and barley	
P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)
P1V	Vernalization sensitivity coefficient (%/d of unfulfilled vernalization)
P5	Thermal time from the onset of linear fill to maturity (°C d)
G1	Kernel number per unit stem + spike weight at anthesis (#/g)
G2	Potential kernel growth rate (mg/(kernel d))
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)
PHINT	Thermal time between the appearance of leaf tips (°C d)

The CERES-Maize, Wheat and Barley models were modified for integration into the modular DSSAT–CSM. For these CERES models, the plant life cycle is divided into several phases, which are similar among the crops (Table 5). Rate of development is governed by thermal time, or growing degree-days (GDD), which is computed based on the daily maximum and minimum temperatures. The GDD required to progress from one growth stage to another are either defined as a user input (Table 6), or are computed internally based on user inputs and assumptions about duration of intermediate stages. Cultivar-specific inputs for all DSSAT–CSM CERES models are presented in absolute terms for consistency, a convention change from that followed previously for wheat and barley for which relative values were used. The number of GDD occurring on a calendar day is a function of a triangular or trapezoidal function defined by a base temperature, one or two optimum temperatures, and a maximum temperature above which development does not occur. Daylength may affect the total number of leaves formed by altering the duration of the floral induction phase, and thus, floral initiation. Daylength sensitivity is a cultivar-specific user input. Currently, only temperature and, in some cases, daylength, drive the accumulation of GDD; drought and nutrient stresses currently have no effect. During the vegetative phase, emergence of new leaves is used to limit leaf area development until after a species-dependent number of leaves have appeared. Thereafter, vegetative branching can occur, and leaf area development depends on the availability of assimilates and specific leaf area. Leaf area expansion is modified by daily temperature GDD, and water and nitrogen stress.

Daily plant growth is computed by converting daily intercepted photosynthetically active radiation into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception is computed as a function of LAI, plant population, and row spacing. The amount of new dry matter available for growth each day may also be modified by the most limiting of water or nitrogen stress, and temperature, and is sensitive to atmospheric CO_2 concentration. Above ground biomass has priority for carbohydrate, and at the end of each day, carbohydrate not used for above ground biomass is allocated to roots. Roots must receive, however, a specified stage-dependent minimum of the daily carbohydrate available for growth. Leaf area is converted into new leaf weight using empirical functions.

Kernel numbers per plant are computed during flowering based on the cultivar's genetic potential, canopy weight, average rate of carbohydrate accumulation during flowering, and temperature, water and nitrogen stresses. Potential kernel number is a user-defined input for specific cultivars. Once the beginning of grain fill is reached, the model computes daily grain growth rate based on a user-specified cultivar input (Table 6) defined as the potential kernel growth rate (mg/(kernel d)). Daily growth rate is modified by temperature and assimilate availability. If the daily pool of carbon is insufficient to allow growth at the potential rate, a fraction of carbon can be remobilized from the vegetative to reproductive sinks each day. Kernels are allowed to grow until physiological maturity is reached. If the plant runs out of resources, however, growth is terminated prior to physiological maturity. Likewise, if the grain growth rate is reduced below a threshold value for several days, growth is also terminated. Readers are referred to other papers for additional details on these CERES models ((Jones and Kiniry, 1986; Ritchie and Otter, 1985; Ritchie et al., 1998).

3.6. Management module

The management module determines when field operations are performed by calling sub modules. Currently, these operations are planting, harvesting, applying inorganic fertilizer, irrigating and applying crop residue and organic material. These operations can be specified by users in the standard 'experiment' input file (Hunt et al., 2001). Users specify whether any or all of the operations are to be automatic or fixed based on input dates or days from planting. Conditions that cause automatic planting within the interval of time are soil water content averaged over a specified depth (i.e. 30 cm) and soil temperature at a specified depth to be between specified limits. Harvesting can occur on given dates, when the crop is mature, or when soil water conditions in the field are favorable for machine operation. Irrigation can be applied on specific dates with specified irrigation amount or can be controlled by the plant available water. If plant available water drops below a specified fraction of water holding capacity in an irrigation management depth, an irrigation event is triggered. The irrigation amount applied can be either a fixed amount or it can refill the profile to the management depth. Similarly, fertilizer can be applied on fixed dates in specified amounts, or the applications can optionally be controlled by plant needs for nitrogen via the nitrogen stress variable from the Plant module. Crop residue and organic fertilizer, such as manure, is applied either at the start of simulation, after harvesting the crop or on fixed dates similar to inorganic fertilizer applications. These management options allow users a great deal of flexibility for simulating experiments that were conducted in the past for model evaluation and improvement and for simulating optional management systems for different applications. The management file also provides scope to define multiple crops and management strategies for crop rotations and sequencing.

3.7. Pest module

The Pest module was developed for the CROPGRO models by Batchelor et al. (1993), following the approach described by Boote et al. (1983, 1993). It allows users to input field observations and scouting data on insect populations or damage to different plant parts, disease severity on different plant tissues, and physical damage to plants or plant components to simulate the effects of specified pest and diseases on growth and yield. Feedbacks on plant growth processes are through leaf area reduction, assimilate loss, loss of leaves, fruit, stems, or roots, and inactivation of the photosynthetic capacity of leaves (Boote et al., 1983). This feature has been used successfully for soybean, peanut, and tomato in the past (e.g. Boote et al., 1983, 1993; Batchelor et al., 1993),

Table 7
Contents of minimum data sets for operation and evaluation of the DSSAT–CSM

(a) For operation of model	
Site	Latitude and longitude, elevation; average annual temperature; average annual amplitude in temperature
	Slope and aspect; major obstruction to the sun (e.g. nearby mountain); drainage (type, spacing and depth); surface stones (coverage and size)
Weather	Daily global solar radiation, maximum and minimum air temperatures, precipitation
Soil	Classification using the local system and (to family level) the USDA-NRCS taxonomic system
	Basic profile characteristics by soil layer: in situ water release curve characteristics (saturated drained upper limit, lower limit); bulk density, organic carbon; pH; root growth factor; drainage coefficient
Initial conditions	Previous crop, root, and nodule amounts; numbers and effectiveness of rhizobia (nodulating crop)
	Water, ammonium and nitrate by soil layer
Management	Cultivar name and type
	Planting date, depth and method; row spacing and direction; plant population
	Irrigation and water management, dates, methods and amounts or depths
	Fertilizer (inorganic) and inoculant applications
	Residue (organic fertilizer) applications (material, depth of incorporation, amount and nutrient concentrations)
	Tillage
	Environment (aerial) adjustments
	Harvest schedule
(b) For evaluation of models	
	Date of emergence
	Date of flowering or pollination (where appropriate)
	Date of onset of bulking in vegetative storage organ (where appropriate)
	Date of physiological maturity
	LAI and canopy dry weight at three stages during the life cycle
	Canopy height and breadth at maturity
	Yield of appropriate economic unit (e.g. kernels) in dry weight terms
	Canopy (above ground) dry weight to harvest index (plus shelling percentage for legumes)
	Harvest product individual dry weight (e.g. weight per grain, weight per tuber)
	Harvest product number per unit at maturity (e.g. seeds per spike, seeds per pod)
	Harvest product number per unit at maturity (e.g. seeds per spike, seeds per pod)
	Soil water measurements vs. time at selected depth intervals
	Soil nitrogen measurements vs. time
	Soil C measurements vs. time, for long-term experiments
	Damage level of pest (disease, weeds, etc.) infestation (recorded when infestation first noted, and at maximum)
	Number of leaves produced on the main stem
	N percentage of economic unit
	N percentage of non-economic parts

and now this capability is accessible to all crops modeled in the DSSAT–CSM.

4. Data requirements

The DSSAT models require the minimum data set for model operation. The contents of such a dataset have been defined based on efforts by workers in IBSNAT and ICASA (Jones et al., 1994; Hunt and Boote, 1998; Hunt et al., 2001), and are shown in Table 7. They encompass data on the site where the model is to be operated, on the daily weather during the growing cycle, on the characteristics of the soil at the start of the growing cycle or crop sequence, and on the management of the crop (e.g. seeding rate, fertilizer applications, irrigations).

Required weather data (Table 7a) encompass daily records of total solar radiation incident on the top of the crop canopy, maximum and minimum air temperature above the crop, and rainfall. However, it is recognized that all required weather data for a particular site and a particular time period are often not available. In such cases, the integrity of the minimum data set is maintained by calculating surrogate values or using data from nearby sites. To calculate surrogate values, statistics of the climate at a particular site are necessary and may thus be required.

The DSSAT–CSM requires information on the water holding characteristics of different soil layers. It needs a root weighting factor that accommodates the impact of several adverse soil factors on root growth in different soil layers, such as soil pH, soil impedance, and salinity. Additional soil parameters are needed for computing surface runoff, evaporation from the soil surface, and drainage (Ritchie, 1972). Initial values of soil water, nitrate and ammonium are needed as well as an estimate of the above- and below-ground residues from the previous crop. All aspects of crop management including modifications to the environment (e.g. photoperiod extension) as imposed in some crop physiology studies, are needed. Typical crop management factors include planting date, planting depth, row spacing, plant population, fertilization, irrigation and inoculation. Plant bed configuration and bund height is also necessary for some crops. The DSSAT–CSM also requires coefficients for the genotypes involved (Hunt, 1993; Ritchie, 1993), as described earlier with examples in Tables 4 and 6.

5. Software implementation, distribution policy

The DSSAT–CSM is a new implementation of the individual crop models contained in DSSAT v3.5. Its first release was in June 2002 where it was used in a course on application of CSMs at the University of Florida. Thus, although this version of the DSSAT models has not achieved widespread distribution yet, it is the latest release of the widely used DSSAT suite of crop models in a much more integrated format that was designed in part for better capabilities for simulating cropping systems. At the time of publication, this DSSAT–CSM was available from the same source as DSSAT v3.5, as described below.

For over 5 years, DSSAT v3.5 DSSAT (Tsuji et al., 1994; Hoogenboom et al., 1999) has been distributed through the International Consortium for Agricultural Systems Applications (ICASA) for a small fee; order forms are at the ICASA web site (www.ICASAnet.org). ICASA supports an open code policy and encourages collaborating scientists to evaluate and improve the source code. Source code of the cropping systems models is available upon request for registered users of DSSAT. ICASA also maintains a list server to exchange information between users and developers of DSSAT. Currently there are more than 325 members of this list server. Information on how to subscribe to the DSSAT list server and archives of frequently asked questions can also be found at the ICASA web site. Technical support is provided by the individual developers of the CSM and is normally conducted via electronic mail. ICASA considers DSSAT to be an open platform and encourages active participation by the users' community to help with the improvement and advancement of its various models, modules, tools and application programs.

6. Model evaluation and testing

Evaluation involves comparison of model outputs with real data and a determination of suitability for an intended purpose. It is useful to think of model evaluation as a documentation of its accuracy for specific predictions in specified environments, with appropriate consideration given to possible errors in input variables or evaluation data. Essential parts of any minimum data set for evaluation are: (1) a complete record of the information required to run the model (Table 7a), and (2) field information on the aspect(s) for which the model is being validated (Table 7b). The data sets should not have been used previously for calibration and should represent the complete array of environments and crop sequences for which the model will be applied. In the past, it has often been difficult to obtain enough data sets for effective evaluation, and to this end the DSSAT community has endeavoured to assemble a collection of datasets that can be used on an ongoing basis for model evaluation. Testing over diverse regions is valuable to expose models to new and different environments and test model robustness as Piper et al. (1998) did.

DSSAT model developers and other scientists have tested the models against various single factors, such as water, nitrogen, cultivar or planting date choice, and temperature. Since the DSSAT–CSM has just been released, we describe here evaluation of the crop models as they existed in the previous versions of DSSAT, the most recent being DSSAT v3.5. This is appropriate since component models in DSSAT–CSM are the same as those in DSSAT v3.5, reprogrammed and integrated together. The only new addition was the incorporation of the CENTURY module to facilitate more accurate cropping system analysis (Gijsman et al., 2002). Testing of these models has occurred at the level of processes, in terms of seasonal dynamics of leaf area, crop biomass, or ET over time, or in terms of final yield variables such as total biomass or grain yield. Statements of adequacy of model prediction include calculation of standard errors, root mean square error, and slope and intercept of regression of observed vs. predicted variables. Additionally, many studies have evaluated model performance, particularly yield, relative to observations from farmers' fields or other tests of cropping systems where many factors may vary (e.g. Boote et al., 1989). This latter approach was used in the international study of climate change impacts on agriculture described by Rosenzweig et al. (1995). In that study, researchers first evaluated model performance using data from cropping systems currently used in their respective countries, then used the models to assess the potential impacts of climate change on their cropping systems using different climate scenarios. Many of the studies referenced in Table 8 evaluated the models for the applications shown.

Recent examples of model evaluation for two crops (corn and soybean) demonstrate the use of different model evaluation approaches for different purposes. Braga (2000) evaluated the ability of the CERES-Maize model to accurately describe the spatial variability in maize yields over 2 years for use in precision agriculture research and decision support. He precisely measured soil water holding parameters in 40 locations in a farmer's field in Michigan, including initial conditions at planting during each of 2 years. Fig. 3 shows a comparison of simulated vs. observed maize yields for the 40 locations over 2 years, showing that the model reproduced observed grain yields for these conditions when accurate soil, weather and cultivar information was available. Mavromatis et al. (2002) demonstrated the value of using routinely collected data from yield trials for both estimating cultivar characteristics and for evaluation. They used yield trial data from Georgia and North Carolina to show the robustness of the CROPGRO-Soybean model predictions across regions. They first used the yield trial data from Georgia to estimate cultivar coefficients for a number of cultivars, then used coefficients estimated from North Carolina yield trial data to predict the performance of the same cultivars in Georgia (Fig. 4). Results in Fig. 4(b) demonstrate the ability of the CROPGRO-Soybean model in DSSAT to predict soybean yields in environments different from those used to estimate the coefficients; on average simulated yields were within 2.5% of mean observed yields at each location.

Another important issue in model testing involves evaluation of simulations under different conditions as models undergo modifications during maintenance or enhancements. Modifications to some scientific relationships in a model may cause unexpected responses or bugs in the code that may go unnoticed unless a rigorous testing procedure is carried out. During the creation of the DSSAT–CSM, modifications to the original CERES and CROPGRO code were required, so software was developed to automatically compare simulated results from the new modular models with those obtained from the latest released versions in DSSAT v3.5 (C. Porter, unpublished). This software invokes two versions of models for the same crop (e.g. soybean) as changes are made to make sure that results are the same or to understand the reasons for changes that occur as a result of modifications. A standard set of real

Table 8
List of various types of applications of the DSSAT crop models and example references that describe these applications in detail, organized by continent on which the studies were conducted

Region	Type of application	References
Africa	Crop management	Fechter et al. (1991), Mbabaliye and Wojtkowski (1994), Vos and Mallett (1987), Wafula (1995)
	Fertilizer management	Jagtap et al. (1999), Singh et al. (1993), Thornton et al. (1995), Keating et al. (1991)
	Irrigation management	Kamel et al. (1995), MacRobert and Savage (1998)
	Precision management	Booltink et al. (2001)
	Climate change	Muchena and Iglesias (1995)
	Climate variability	Phillips et al. (1998)
	Food security	Pisani (1987), Thornton et al. (1997)
Asia	Crop management	Alagarswamy et al. (2000), Jintrawet (1995), Singh et al. (1994a,b), Salam et al. (2001)
	Fertilizer management	Godwin et al. (1994)
	Irrigation management	Hundal and Prabhjyot-Kaur (1997)
	Pest management	Luo et al. (1997), Pinnschmidt et al. (1995)
	Climate change	Jinghua and Erda (1996), Lal et al. (1998, 1999), Luo et al. (1995, 1998), Singh and Godwin (1990)
	Climate variability	Alocilja and Ritchie (1990), Gadgil et al. (1999)
	Yield forecasting	Kaur and Hundal (1999), Singh et al. (1999)
	Sustainability	Singh et al. (1999a,b)
Europe	Crop management	Hunkár (1994), Pfeil et al. (1992a,b), Ruiz-Nogueria et al. (2001), Sau et al. (1999), Zalud et al. (2000)
	Fertilizer management	Gabrielle and Kengni (1996), Gabrielle et al. (1998), Zalud et al. (2001)
	Irrigation management	Ben Nouna et al. (2000), Castrignano et al. (1998), Gerdes et al. (1994)
	Tillage management	Castrignano et al. (1997)
	Variety evaluation	Brisson et al. (1989), Colson et al. (1995)
	Precision farming	Booltink and Verhagen (1997), Booltink et al. (2001)
	Environmental pollution	Kovács and Németh (1995)
	Climate change	Alexandrov and Hoogenboom (2001), Iglesias et al. (2000), Semenov et al. (1996), Wolf et al. (1996)
	Yield forecasting	Landau et al. (1998), Saarikko (2000)
	Sustainability	Hoffmann and Ritchie (1993)
North America	Crop management	Egli and Bruening (1992), Jame and Cutforth (1996), Sexton et al. (1998)
	Fertilizer management	Beckie et al. (1995), Hodges (1998)
	Irrigation management	Epperson et al. (1993), Hook (1994), McClendon et al. (1996), Steele et al. (2000), Swaney et al. (1983)
	Pest management	Barbour et al. (1994), Barbour and Bridges (1995), Batchelor et al. (1993), Boote et al. (1993), Lacey et al. (1989), Mishoe et al. (1984)
	Tillage management	Andales et al. (2000)
	Variety evaluation	Irmak et al. (1999), Manrique et al. (1990), Mavromatis et al. (2001), Piper et al. (1996a,b, 1998)
	Genomics	Boote and Tollenaar (1994), Boote et al. (2001), Hoogenboom et al. (1997), White and Hoogenboom (1996)

Table 8 (*Continued*)

Region	Type of application	References
	Precision agriculture	Han et al. (1995), Sadler et al. (2000), Paz et al. (1998, 1999), Irmak et al. (2001), Paz et al. (2001a,b)), Seidl et al. (2001)
	Environmental pollution	Gerakis and Ritchie (1998), Pang et al. (1998)
	Climate change	Hatch et al. (1999), Mearns et al. (2001), Rosenzweig and Tubiello (1996), Southworth et al. (2000), Tubiello et al. (1995, 2001), Boote et al. (1997)
	Climate variability	Hansen and Jones (2000), Jones et al. (2000), Mearns et al. (1996)
	Yield forecasting	Carbone (1993), Carbone et al. (1996), Chipanshi et al. (1997, 1999), Duchon (1986), Georgiev and Hoogenboom (1999), Moulin and Beckie (1993)
	Sustainability	Hasegawa et al. (1999, 2000), Quemada and Cabrera (1995), Wagner-Riddle et al. (1997)
	Space technology	Fleisher et al. (2000)
	Education	Cabrera (1994), Meisner et al. (1991)
Central and South America	Crop management	Savin et al. (1995), Travasso and Magrin (1998)
	Irrigation management	Heinemann et al. (2000)
	Precision management	Booltink et al. (2001)
	Variety evaluation	Castelan Ortega et al. (2000), Ferreyra et al. (2000), White et al. (1995)
	Climate change	Baethgen (1997), Conde et al. (1997), Diaz et al. (1997), Magrin et al. (1997), Maytin et al. (1995)
	Climate variability	Messina et al. (1999), Podesta et al. (2002), Ferreyra et al. (2001), Royce et al. (2002)
	Yield forecasting	Meira and Guevara (1997), Travasso et al. (1996)
	Sustainability	Bowen et al. (1992)
	Education	Ortiz (1998)

and hypothetical experiments are simulated, covering a wide range of conditions, to compare with observed data and to evaluate responses to temperature, solar radiation, planting date, and other factors. This software was used in our efforts to develop the modular DSSAT–CSM to ensure that the scientific integrity of the models was maintained. This software will be made available in the next release of DSSAT so that researchers can test any changes that they might make to the models. The DSSAT–CSM developers will use it for quality control purposes in maintaining and revising the model.

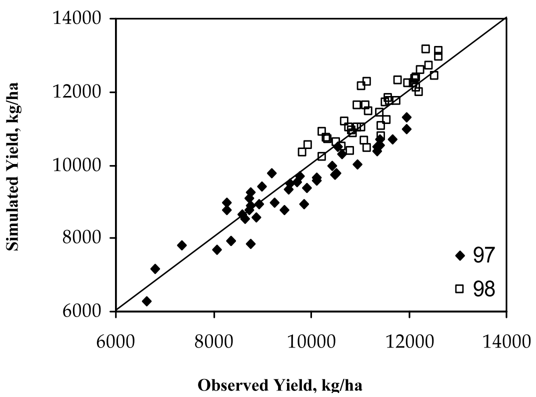

Fig. 3. Simulated versus observed maize grain yield over two years using field-measured, spatially varying soil parameters in Michigan (Braga, 2000).

7. Example applications

The DSSAT crop models have been widely used over the last 15 years by many researchers for many different applications. Many of these applications have been done to study management options at study sites, including fertilizer, irrigation, pest management, and site-specific farming. These applications have been conducted by agricultural researchers from different disciplines, frequently working in teams to integrate cropping

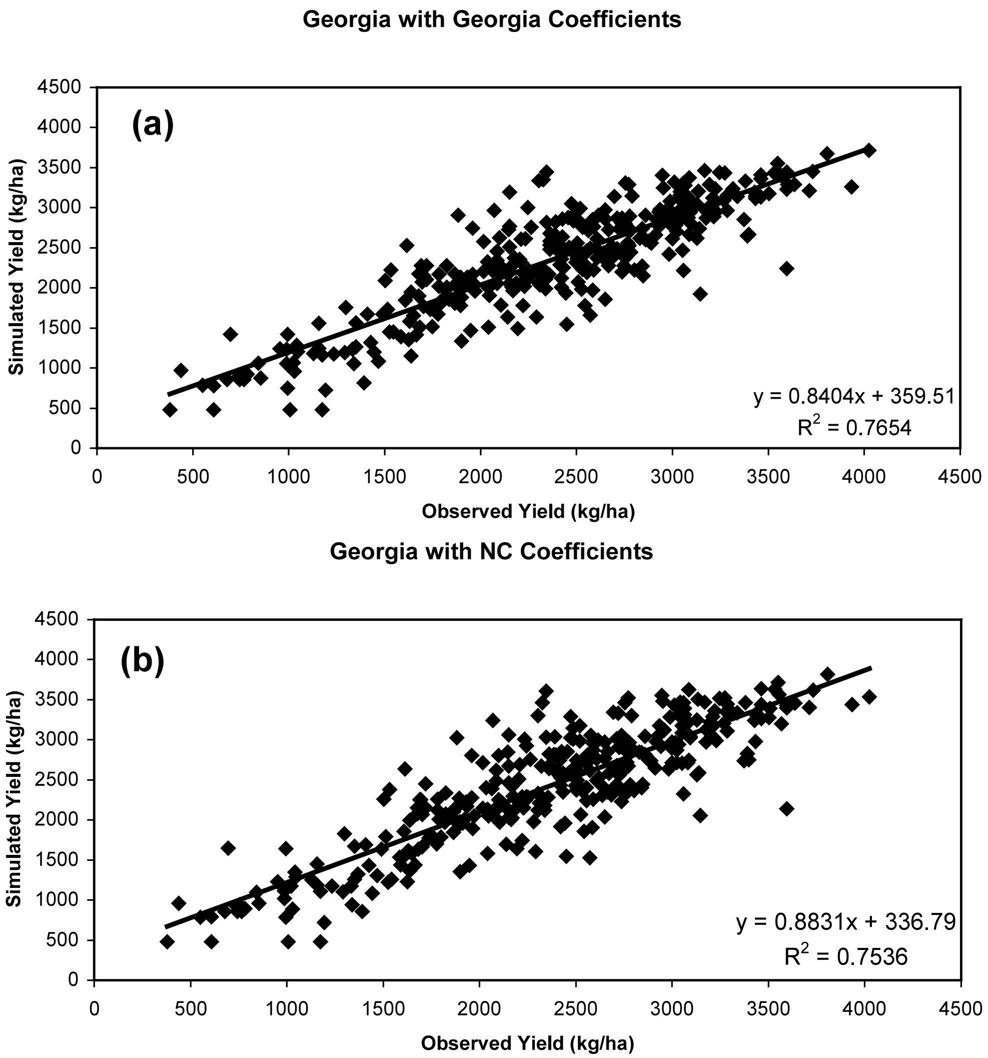

Fig. 4. Simulated vs. observed yields for soybean yield trials in Georgia in which (a) Georgia data were used to estimate cultivar coefficients, and (b) North Carolina data were used to estimate cultivar coefficients (Mavromatis et al., 2002).

systems analysis using models with field agronomic research and socioeconomic information to answer complex questions about production, economics, and the environment.

An important aspect of many of these studies is a consideration that weather influences the performance of crops, interacting in complex ways with soil and management. Researchers have thus applied these models to study uncertainty in crop production associated with weather variability and the associated economic risks that farmers face under such climate variability. Researchers from all continents have used these models in studying potential impacts of climate change on agricultural production (Rosenzweig et al., 1995). The models have also been widely used in studying the potential use of climate forecasts for improving management of different cropping systems, and the value and risks associated with the use of this information. Table 8 lists references that describe some of these applications, organized by continent and application topic.

In addition to research applications, the DSSAT and its crop models have been used in teaching, both in continuing education courses and in formal university courses at graduate and undergraduate levels (Tsuji et al., 1998). There also have been attempts to use these models in advising farmers (through extension services and the private sector). In one application, described by Welch et al. (2002), an agricultural company has implemented versions of three of the DSSAT v3.5 models in a comprehensive farmer support software package that is being used by private consultants. This software package, called PCYield, includes CROPGRO-Soybean, CERES-Maize and CERES-Wheat models. PCYield is available to clients of the company via the Internet along with daily weather data for specific farm locations. It has a very simple user interface to allow private crop consultants to operate them for any of their farmer clients (http://www.mPower3.com).

The applications referred to in Table 8 provide a broad overview of the many studies that have used the DSSAT and its crop models. These were conducted before the new modular DSSAT–CSM was developed. Thus, many of these applications have focused on single crops instead of cropping systems. Since the DSSAT–CSM simulates crop and soil processes the same as DSSAT v3.5 (except for the new CENTURY-based soil C and N module), the current version has the same scientific capabilities that were used in most of these previous studies. However, the new DSSAT–CSM opens the way for more effective research on cropping systems (Gijsman et al., 2002), and it opens the way for more effective scientific improvements than ever before due to overcoming many hurdles imposed by the structure of previous versions.

8. Closing the loop between development and application

As shown in the previous section, researchers have been applying DSSAT crop models for many purposes. However, as more experience has been gained by the scientific community in using these models, the demands have increased beyond those that motivated many of these studies. In many past studies, researchers accepted the crop and soil models in DSSAT as they were, but many studies showed that improvements were needed in various parts of the models. In some cases, researchers modified the code to create their own versions of crop models, but such efforts were complicated by the design of the models themselves and by the lack of adequate documentation in some cases. The re-design of the DSSAT–CSM was undertaken to help overcome some of these problems as well as to facilitate an efficient evolution for broader and more advanced applications in the future. Although the DSSAT–CSM is new, researchers are already adding new modules for pest dynamics (J. Koo, personal communication), models for new crops (O. Daza, personal communication). We expect that the modular structure, open code, testing software, the documentation, and instructions for modifying or adding modules and embedding DSSAT–CSM into other software will help close the gap between development and research applications. This includes the use of CSMs for policy; our experience indicates that researchers will be part of the process of cropping system applications for informing policy makers.

A more difficult issue is, however, the gap that exists between CSMs and their applications for decision support at a farm level. There are scientific and technical reasons for this gap. Many CSMs currently do not include factors that may limit growth and yield of crops grown under field conditions, such as different pests or other soil constraints. Gaining an understanding of these factors, how they interact with environment and management, and expanding model capabilities to include them is a challenge for agricultural scientists (Boote et al., 1996). Even if all of these factors were included in models, there would still be enormous difficulties in providing data inputs necessary to simulate these factors and their effects on crop production at a site. Our own experience with PCYield (Welch et al., 2002) indicated that crop consultants will use CSMs if they add value to the services that consultants provide to farmers, are easy to use, inexpensive in terms of dollar and time costs, and have ready access to farm-specific and industry-specific information. Although some progress was made to overcome some impediments, such as access to daily weather data for specific farms (Welch et al., 2002) and software for calculating genetic coefficients using yield trial data (Mavromatis et al., 2001, 2002) others still exist. Technically, the major impediments are access to accurate site-specific soil and management information as well as high quality software that addresses relevant issues and appropriately embeds CSMs. However, the use of CSMs in software for decision support may be more constrained by social factors (McCown, 2001). Overcoming these constraints are likely to require consistent social interactions between advisors who use models and people to whom they give advice.

Looking ahead, we envision many applications in which the DSSAT–CSM will be integrated with other models and information for many research purposes. We are already developing special drivers for integrating the CSM with GIS for diagnosing causes of yield variability in precision agriculture fields (Paz et al., 2001a; Irmak et al., 2001) and for prescribing variable management (Paz et al., 2001b) and for linking with other models, such as for water quality and mixed crop-livestock farming system analysis. The DSSAT–CSM will continue to evolve as these new applications are developed and as we learn how to effectively incorporate other factors for more comprehensive agricultural systems analyses.

References

Alagarswamy, G., Singh, P., Hoogenboom, G., Wani, S.P., Pathak, P., Virmani, S.M., 2000. Evaluation and application of the CROPGRO-Soybean simulation model in vertic inceptisol. Agricultural Systems 63, 19–32.

Alexandrov, V.A., Hoogenboom, G., 2001. The impact of climate variability and change on crop yield in Bulgaria. Agricultural and Forest Meteorology 104, 315–327.

Alocilja, E.C., Ritchie, J.T., 1990. The application of SIMOP-T2:RICE to evaluate profit and yield-risk in upland-rice production. Agricultural Systems 33, 315–326.

Andales, A.A., Batchelor, W.D., Anderson, C.E., Farnham, D.E., Whigham, D.K., 2000. Incorporating tillage effects into soybean model. Agricultural Systems 66, 69–98.

Baethgen, W.E., 1997. Vulnerability of the agricultural sector of Latin America to climate change. Climate Research 9, 1–7.

Barbour, J.C., Bridges, D.C., 1995. A model of competition for light between peanut (*Arachis hypogaea*) and broadleaf weeds. Weed Science 43 (2), 247–257.

Barbour, J.C., Bridges, D.C., Nesmith, D.S., 1994. Peanut acclimation to simulated shading by weeds. Agronomy Journal 86 (5), 874–880.

Batchelor, W.D., Jones, J.W., Boote, K.J., Pinnschmidt, H.O., 1993. Extending the use of crop models to study pest damage. Transactions of the ASAE 36 (2), 551–558.

Beckie, H.J., Moulin, A.P., Campbell, C.A., Brandt, S.A., 1995. Testing effectiveness of four simulation models for estimating nitrates and water in two soils. Canadian Journal of Soil Sciences 75, 135–143.

Ben Nouna, B., Katerji, N., Mastrorilli, M., 2000. Using the CERES-Maize model in a semi-arid Mediterranean environment. Evaluationof model performance. European Journal of Agronomy 13 (4), 309–322.

Booltink, H.W.G., Verhagen, J., 1997. Using decision support systems to optimize barley management on spatial variable soil. In: Kropff, M., et al. (Eds.), Applications of Systems Approaches at the Field Level, vol. 2. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 219–233.

Booltink, H.W.G., van Alphen, B.J., Batchelor, W.D., Paz, J.O., Stoorvogel, J.J., Vargas, R., 2001. Tools for optimizing management of spatially-variable fields. Agricultural Systems 70, 445–476.

Boote, K.J., Batchelor, W.D., Jones, J.W., Pinnschmidt, H., Bourgeois, G., 1993. Pest damage relations at the field level. In: Penning de Vries, F.W.T., et al. (Eds.), Systems Approaches for Agricultural Development. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Boote, K.J., Bennett, J.M., Jones, J.W., Jowers, H.E., 1989. On-farm testing of peanut and soybean models in Florida. ASAE P No. 89-4040. Am. Soc. Agr. Engr. (ASAE), St. Joseph, MI, pp. 54.

Boote, K.J., Jones, J.W., Hoogenboom, G., 1998a. Simulation of crop growth: CROPGRO model. In: Peart, R.M., Curry, R.B. (Eds.), Agricultural Systems Modeling and Simulation (Chapter 18). Marcel Dekker, Inc, New York, pp. 651–692.

Boote, K.J., Jones, J.W., Hoogenboom, G., Pickering, N.B., 1998b. The CROPGRO model for grain legumes. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 99–128.

Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential uses and limitations of crop models. Agronomie Journal 88, 704–716.

Boote, K.J., Mínguez, M.I., Sau, F., 2002. Adapting the CROPGRO-legume model to simulate growth of faba bean. Agronomy Journal 94, 743–756.

Boote, K.J., Pickering, N.B., 1994. Modeling photosynthesis of row crop canopies. HortScience 29, 1423–1434.

Boote, K.J., Kropff, M.J., Bindraban, P.S., 2001. Physiology and modeling of traits in crop plants: implications for genetic improvement. Agricultural Systems 70, 395–420.

Boote, K.J., Jones, J.W., Mishoe, J.W., Berger, R.D., 1983. Coupling pests to crop growth simulators to predict yield reductions. Phytopathology 73 (11), 1581–1587.

Boote, K.J., Jones, J.W., Mishoe, J.W., Wilkerson, G.G., 1986. Modeling growth and yield of groundnut. Agrometeorology of Groundnut: Proceedings of an International Symposium, ICRISAT Sahelian Center, Niamey, Niger. 21–26 Aug, 1985, ICRISAT, Patancheru, A.P. 502 324, India, pp. 243–254.

Boote, K.J., Pickering, N.B., Allen, L.H., Jr., 1997. Plant modeling: advances and gaps in our capability to project future crop growth and yield in response to global climate change. In: Allen, L.H., Jr., Kirkham, M.B., Olszyk, D.M., Whitman, C.E. (Eds.), Advances in Carbon Dioxide Effects Research (Special Publication No. 61). ASA-CSSA-SSSA, Madison, WI, pp. 179–228.

Boote, K.J., Tollenaar, M., 1994. Modeling genetic yield potential. In: Boote, K.J., Bennett, J.M., Sinclair, T.R., Paulsen, G.M. (Eds.), Physiology and Determination of Crop Yield. ASA-CSSA-SSSA, Madison, WI, pp. 533–565.

Bowen, W.T., Jones, J.W., Thornton P.K., 1992. Crop simulation as a potential tool for evaluating sustainable land management. Utilization of Soil Survey Information for Sustainable Land Use Proceedings: 11–24 July.

Braga, R., 2000. Predicting the spatial pattern of grain yield under water limiting conditions. PhD Dissertation, Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL, pp. 176.

Brisson, N., Bona, S., Bouniols, A., 1989. A soybean crop simulation model: validation and adaptation to varieties cultivated in southern Europe. Agronomie 9, 27–36.

Cabrera, M.L., 1994. N-show: an educational computer program that displays dynamic graphs of nitrogen in soil. Journal of Natural Resources and Life Scince Education 23 (1), 43–45.

Carbone, G.J., 1993. Considerations of meteorological time-series in estimating regional-scale crop yield. Journal of Climate 6 (8), 1607–1615.

Carbone, G.J., Narumalani, S., King, M., 1996. Application of remote sensing and GIS technologies with physiological crop models. American Society for Photogrammetry and Remote Sensing 62 (2), 171–179.

Castrignano, A., Colucci, R., Degiorgio, D., Rizzo, V., Stelluti, M., 1997. Tillage effects on plant extractable soil–water in a silty clay vertisol in southern Italy. Soil and Tillage Research 40 (3–4), 227–237.

Castrignano, A., Katerji, N., Karam, F., Mastrorilli, M., Hamdy, A., 1998. A modified version of CERES-Maize model for predicting crop response to salinity stress. Ecological Modelling 111 (2–3), 107–120.

Castelan Ortega, O.A., Fawcett, R.H., Arriaga Jordan, C.M., Smith, A.J., 2000. Evaluation of the CERES-Maize model in simulating Campesino farmer yields in the highlands of central Mexico. Experimental Agriculture 36 (4), 479–500.

Chipanshi, A.C., Ripley, E.A., Lawford, R.G., 1997. Early prediction of spring wheat yields in Saskatchewan from current and historical weather data using the CERES-wheat model. Agricultural and Forest Meteorology 84 (3–4), 223–232.

Chipanshi, A.C., Ripley, E.A., Lawford, R.G., 1999. Large-scale simulation of wheat yields in a semi-arid environment using a crop-growth model. Agricultural Systems 59 (1), 57–66.

Colson, J., Bouniols, A., Jones, J.W., 1995. Soybean reproductive development: adapting a model for European cultivars. Agronomy Journal 87, 1129–1139.

Conde, C., Liverman, D., Flores, M., Ferrer, R., Araujo, R., Betancourt, E., Villarreal, G., Gay, C., 1997. Vulnerability of rainfed maize crops in Mexico to climate change. Climate Research 9, 17–23.

Diaz, R.A., Magrin, G.O., Travasso, M.I., Rodriguez, R.O., 1997. Climate change and its impact on the properties of agricultural soils in the Argentinean rolling pampas. Climate Research 9, 25–30.

Doorenbos, J., Pruitt, W.D., 1977. Guidelines for predicting crop water requirements. Food and Agriculture Organization of the United Nations, Rome. Irrigation and Drainage Paper No. 24.

Duchon, C.E., 1986. Corn yield prediction using climatology. Journal of Climate and Applied Meteorology 25 (5), 581–590.

Egli, D.B., Bruening, W., 1992. Planting date and soybean yield: evaluation of environmental effects with a crop simulation model: SOYGRO. Agricultural and Forest Meteorology 62 (1–2), 19–29.

Epperson, J.E., Hook, J.E., Mustafa, Y.R., 1993. Dynamic programming for improving irrigation scheduling strategies of maize. Agricultural Systems 42, 85–101.

Fechter, J., Allison, B.E., Sivakumar, M.V.K., van der Ploeg, R.R., Bley, J., 1991. An evaluation of the SWATRER and CERES-Millet models for southwest Niger. In: Sivakumar, M.V.K., Wallace, J.S., Renard, C., Giroux, C. (Eds.), Soil Water Balance in the Sudano-Sahhelian Zone. International Association of Hydrological Sciences, Wallingford, pp. 505–513.

Ferreyra, R.A., Pachepsky, L.B., Collino, D., Acock, B., 2000. Modeling peanut leaf gas exchange for the calibration of crop models for different cultivars. Ecological Modelling 131 (2–3), 285–298.

Ferreyra, R.A., Podesta, G.P., Messina, C.D., Letson, D., Dardanelli, J., Guevera, E., Meira, S., 2001. A linked-modeling framework to estimate maize production risk associated with ENSO-related climate variability in Argentina. Agricultural and Forest Meteorology 107, 177–192.

Fleisher, D.H., Cavazzoni, J., Giacomelli, G.A., Ting K.C., 2000. Adaption of SUBTOR for hydroponic, controlled environment white potato production. ASAE Paper 00-4089. American Society of Agricultural Engineers, St. Joseph, MI.

Gabrielle, B., Kengni, L., 1996. Analysis and field-evaluation of the CERES models' soil components: nitrogen transfer and transformations. Soil Science Society of American Journal 60, 142–149.

Gabrielle, B., Denoroy, P., Gosse, G., Justes, E., Andersen, M.N., 1998. Development and evaluation of a CERES-type model for winter oilseed rape. Field Crops Research 57 (1), 95–111.

Gadgil, S., Seshagiri Rao, P.R., Sridhar, S., 1999. Modelling impact of climate variability on rainfed groundnut. Current Science 76, 557–569.

Geng, S., Penning de Vries, F.W.T., Supit, I., 1986. A simple method for generating daily rainfall data. Agricultural and Forest Meteorology 36, 363–376.

Geng, S., Auburn, J., Brandstetter, E., Li, B., 1988. A program to simulate meteorological variables. Documentation for SIMMETEO. Agronomy Report No. 204. University of California, Davis Crop Extension, Davis, CA.

Georgiev, G.A., Hoogenboom, G., 1999. Near real-time agricultural simulations on the web. Simulation 73 (1), 22–28.

Gerakis, A., Ritchie, J.T., 1998. Simulation of atrazine leaching in relation to water-table management using the CERES model. Journal of Environmental Management 52, 241–258.

Gerdes, G., Allison, B.E., Pereira, L.S., 1994. Overestimation of soybean crop transpiration by sap flow measurements under field conditions in central Portugal. Irrigation Science 14 (3), 135–139.

Giraldo, L.M., Lizcano, L.J., Gijsman, A.J., Rivera, B., Franco, L.H., 1998. Adaptation of the DSSAT model for simulation of *Brachiaria decumbens* production. Pasturas Tropicales 20, 2–12.

Gijsman, A.J., Hoogenboom, G., Parton, W.J., Kerridge, P.C., 2002. Modifying DSSAT for low-input agricultural systems, using a soil organic matter—residue module from CENTURY. Agronomy Journal 94 (3), 462–474.

Godwin, D.C., Jones, C.A., 1991. Nitrogen dynamics in soil–plant systems. In: Hanks, J., Ritchie, J.T. (Eds.), Modeling Plant and Soil Systems (Agronomy monograph no. 31). ASA, CSSA, and SSSA, Madison, WI, pp. 287–321.

Godwin, D.C., Singh, U., 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. System Approaches for Sustainable Agricultural Development. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 55–77.

Godwin, D.C., Meyer, W.S., Singh, U., 1994. Simulation of the effect of chilling injury and nitrogen supply on floret fertility and yield in rice. Australian Journal Experimental Agricultural 34, 921–926.

Grimm, S.S., Jones, J.W., Boote, K.J., Herzog, D.C., 1994. Modeling the occurrence of reproductive stages after flowering for four soybean cultivars. Agronomy Journal 86, 31–38.

Grimm, S.S., Jones, J.W., Boote, K.J., Hesketh, J.D., 1993. Parameter estimation for predicting flowering date of soybean cultivars. Crop Scince 33, 137–144.

Han, S., Evans, R.G., Hodges, T., Rawlins, S.L., 1995. Linking a geographic information system with a potato simulation model for site-specific crop management. Journal of Environmental Quality 24, 772–777.

Hansen, J.W., Jones, J.W., 2000. Scaling-up crop models for climate variability applications. Agricultural Systems 65, 43–72.

Hartkamp, A.D., Hoogenboom, G., White, J.W., 2002. Adaptation of the CROPGRO growth model to velvet bean as a green manure cover crop: I. Model development. Field Crops Research 78 (1), 9–25.

Hasegawa, H., Bryant, D.C., Denison, R.F., 2000. Testing CERES model predictions of crop growth and N dynamics, in cropping systems with leguminous green manures in a Mediterranean climate. Field Crops Research 67 (3), 239–255.

Hasegawa, H., Labavitch, J.M., McGuire, A.M., Bryant, D.C., Denison, R.F., 1999. Testing CERES model predictions of N release from legume cover crop residue. Field Crops Research 63, 255–267.

Hatch, U., Jagtap, S., Jones, J., Lamb, M., 1999. Potential effects of climate change on agricultural, water use in the southeast US. Journal of the American Water Resources Association 35, 1551–1561.

Heinemann, A.B., Hoogenboom, G., Georgiev, G.A., de Faria, R.T., Frizzone, J.A., 2000. Center pivot irrigation management optimization of dry beans in humid areas. Transactions of the ASAE 43 (6), 1507–1516.

Hoffmann, F., Ritchie, J.T., 1993. Model for slurry and manure in CERES and similar models. Journal Agronomy and Crop Science 170, 330–340.

Hodges, T., 1998. Water and nitrogen applications for potato: commercial and experimental rates compared to a simulation model. Journal of Sustainable Agriculture 13, 79–90.

Hoogenboom, G., Wilkens, P.W., Thornton, P.K., Jones, J.W., Hunt, L.A., Imamura, D.T., 1999. Decision support system for agrotechnology transfer v3.5. In: Hoogenboom, G., Wilkens, P.W., Tsuji, G.Y. (Eds.), DSSAT version 3, vol. 4 (ISBN 1-886684-04-9). University of Hawaii, Honolulu, HI, pp. 1–36.

Hoogenboom, G., White, J.W., Acosta-Gallegos, J., Gaudiel, R.G., Myers, J.R., Silbernagel, M.J., 1997. Evaluation of a crop simulation model that incorporates gene action. Agronomy Journal 89 (4), 613–620.

Hoogenboom, G., Jones, J.W., Wilkens, P.W., Batchelor, W.D., Bowen, W.T., Hunt, L.A., Pickering, N.B., Singh, U., Godwin, D.C., Baer, B., Boote, K.J., Ritchie, J.T., White, J.W., 1994a. Crop models. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), DSSAT Version 3, vol. 2. University of Hawaii, Honolulu, HI, pp. 95–244.

Hoogenboom, G., White, J.W., Jones, J.W., Boote, K.J., 1994b. BEANGRO: A process-oriented dry bean model with a versatile user interface. Agronomy Journal 86, 182–190.

Hook, J.E., 1994. Using crop models to plan water withdrawals for irrigation in drought years. Agricultural Systems 45, 271–289.

Hundal, S.S., Prabhjyot-Kaur, 1997. Application of the CERES-Wheat model to yield predictions in the irrigated plains of the Indian Punjab. Journal of Agricultural Science 129, 13–18.

Hunkár, M., 1994. Validation of crop simulation model CERES-Maize. Quarterly Journal of Hungarian Meteorology Series 98, 37–46.

Hunt, L.A., 1993. Designing improved plant types: a breeder's viewpoint. In: Penning de Vries, F., Teng, P., Metselaar, K. (Eds.), Systems Approaches for Agricultural Development. Kluwer Academic Press, Boston, pp. 3–17.

Hunt, L.A., Boote, K.J., 1998. Data for model operation, calibration, and evaluation. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, pp. 9–39.

Hunt, L.A., White, J.W., Hoogenboom, G., 2001. Agronomic data: advances in documentation and protocols for exchange and use. Agricultural Systems 70, 477–492.

Iglesias, A., Rosenzweig, C., Pereira, D., 2000. Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. Global Environmental Change 10, 69–80.

International Benchmark Sites Network for Agrotechnology Transfer. 1993. The IBSNAT Decade. Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honoluly, Hawaii.

Irmak, A., Jones, J.W., Mavromatis, T., Welch, S.M., Boote, K.J., Wilkerson, G.G., 1999. Evaluating methods for simulating soybean culitvar responses using cross validation. Agronomy Journal 92, 1140–1149.

Irmak, A., Jones, J.W., Batchelor, W.D., Paz, J.O., 2001. Linking multiple layers of information for diagnosing causes of spatial yield variability. Trans. ASAE 45 (3), 839–849.

Jagtap, S.S., Abamu, F.J., Kling, J.G., 1999. Long-term assessment of nitrogen and variety technologies on attainable maize yields in Nigeria using CERES-maize. Agricultural Systems 60, 77–86.

Jame, Y.W., Cutforth, H.W., 1996. Crop growth-models for decision-support systems. Canadian Journal of Plant Science 76 (1), 9–19.

Jinghua, W., Erda, L., 1996. The impacts of potential climate change and climate variability on simulated maize production in China. Water, Air and Soil Pollution 92, 75–85.

Jintrawet, A., 1995. A decision support system for rapid assessment of lowland rice-based cropping alternatives in Thailand. Agricultural Systems 47, 245–258.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station, Texas.

Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, V.W., Griggs, R.H., 1991. EPIC: an operational model for evaluation of agricultural sustainability. Agricultural Systems 37, 341–350.

Jones J.W. Ritchie, J.T., 1991. Crop growth models In: Hoffman, G.J, Howell, T.A., Solomon, K.H. (Eds.), Management of Farm Irrigation Systems, American Society for Agricultural Engineering, pp. 63–89.

Jones, J.W., 1993. Decision support systems for agricultural development. In: Penning de Vries, F., Teng, P., Metselaar, K. (Eds.), Systems Approaches for Agricultural Development. Kluwer Academic Press, Boston, pp. 459–471.

Jones, J.W., Boote, K.J., Hoogenboom, G., Jagtap, S.S., Wilkerson, G.G., 1989. SOYGRO V5.42, Soybean Crop Growth Simulation Model. User's Guide. Fl. Agric. Exp. Sta., Journal No. 8304. University of Florida, Gainesville. pp. 53.

Jones, J.W., Tsuji, G.Y., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer; DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 157–177.

Jones, J.W., Hansen, J.W., Royce, F.S., Messina, C.D., 2000. Potential benefits of climate forecasting to agriculture. Agriculture Ecosystems and Environment 82, 169–184.

Jones, J.W., Hunt, L.A., Hoogenboom, G., Godwin, D.C., Singh, U., Tsuji, G.Y., Pickering, N.B., Thornton, P.K., Bowen, W.T., Boote, K.J., Ritchie, J.T., 1994. Input and output files. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), Decision Support System for Agrotechnology Transfer (DSSAT) Version 3, vol. 2. University of Hawaii, Honolulu, HI, pp. 1–94.

Jones, J.W., Keating, B.A., Porter, C.H., 2001. Approaches to modular model development. Agricultural Systems 70, 421–443.

Kamel, A., Schroeder, K., Sticklen, J., Rafea, A., Salah, A., Schulthess, U., Ward, R., Ritchie, J.T., 1995. Integrated wheat crop management based on generic task knowledge-based systems and CERES numerical-simulation. AI Applications 9 (1), 17–28.

Kaur, P., Hundal, S.S., 1999. Forecasting growth and yield of groundnut (*Arachis hypogaea*) with a dynamic simulation model 'PNUTGRO' under Punjab conditions. Journal of Agricultural Science 133, 167–173.

Keating, B.A., Godwin, D.G., Watiki, J.M., 1991. Optimising nitrogen inputs in response to climatic risk. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production-Models and Management for the Semi-arid Tropics and Subtropics. CAB Internatinal, Wallingford.

Kovács, G.T., Németh, T., 1995. Testing simulation models for the assessment of crop production and nitrate leaching in Hungary. Agricultural Systems 49, 385–397.

Kraalingen, D.W.G. van, 1990. The FORTRAN version of CSMP MACROS (Modules for Annual CRop Simulation). Simulation reports CABO-TT; nr. 21. Centre for Agrobiological Research and Deptarment of Theoretical Production Ecology, Agricultural University, Wageningen, the Netherlands.

Kraalingen, D.W.G. van, 1991. The FSE system for crop simulation. Simulation reports CABO-TT; nr. 23. Centre for Agrobiological Research and Deptarment of Theoretical Production Ecology, Agricultural University, Wageningen, the Netherlands.

Kraalingen, D.W.G. van. 1995. The FSE system for crop simulation, version 2.1. Quantitative Approaches in Systems Analysis, No. 1, C.T. de Wit Graduate School for Production Ecology and Resource Conservation, Wageningen University, The Netherlands, pp. 58.

Kraalingen, D.W.G. van, Rappoldt C., Van Laar, H.H., 2003. The Fortran simulation translator, a simulation language. European Journal of Agronomy 18, 359–361.

Lacey, D.K., McClendon, R.W., Hook, J.E., Todd, J.W., Womack, H., 1989. Express: An Expert Simulation System for Peanut Insect Pest Management (ASAE Paper 89-7574). American Society of Agricultural Engineers, St Joseph, Michigan.

Lal, M., Singh, K.K., Rathore, L.S., Srinivasan, G., Saseendran, S.A., 1998. Vulnerability of rice and wheat yields in NW India to future changes in climate. Agricultural and Forest Meteorology 89, 101–114.

Lal, M., Singh, K.K., Srinivasan, G., Rathore, L.S., Naidu, D., Tripathi, C.N., 1999. Growth and yield responses of soybean in Madhya Pradesh, India to climate variability and change. Agricultural and Forest Meteorology 93 (1), 53–70.

Landau, S., Mitchell, R.A.C., Barnett, V., Colls, J.J., Craigon, J., Moore, K.L., Payne, R.W., 1998. Testing winter wheat simulation models' predictions against observed UK grain yields. Agricultural and Forest Meteorology 89 (2), 85–99.

Luo, Y., Tebeest, D.O., Teng, P.S., Fabellar, N.G., 1995. Simulation studies on risk analysis of rice leaf blast epidemics associated with global climate-change in several Asian countries. Journal of Biogeography 22 (4–5), 673–678.

Luo, Y., Teng, P.S., Fabellar, N.G., Tebeest, D.O., 1997. A rice-leaf blast combined model for simulation of epidemics and yield loss. Agricultural Systems 53 (1), 27–39.

Luo, Y., Teng, P.S., Fabellar, N.G., TeBeest, D.O., 1998. The effects of global temperature change on rice leaf blast epidemics: a simulation study in three agroecological zones. Agriculture Ecosystems and Environment 68, 187–196.

MacRobert, J.F., Savage, M.J., 1998. The use of a crop simulation model for planning wheat irrigation in Zimbabwe. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 205–220.

Magrin, G.O., Travasso, M.I., Diaz, R.A., Rodriguez, R.O., 1997. Vulnerability of the agricultural systems of Argentina to climate change. Climate Research 9, 31–36.

Manrique, L.A., Hodges, T., Johnson, B.S., 1990. Genetic variables for potato. American Potato Journal 67 (10), 669–683.

Mavromatis, T., Boote, K.J., Jones, J.W., Irmak, A., Shinde, D., Hoogenboom, G., 2001. Developing genetic coefficients for crop simulation models with data from crop performance trials. Crop Science 41, 40–51.

Mavromatis, T., Boote, K.J., Jones, J.W., Wilkerson, G.G., Hoogenboom, G., 2002. Repeatability of model genetic coefficients derived from soybean performance trials cross different states. Crop Sci. 42, 76–89.

Maytin, C.E., Acevedo, M., Jaimez, R., Andressen, R., Harwell, M.A., Robock, A., Azocar, A., 1995. Potential effects of global climatic-change on the phenology and yield of maize in Venezuela. Climatic Change 29 (2), 189–211.

Mbabaliye, T., Wojtkowski, P.A., 1994. Problems and perspectives on the use of a crop simulation model in an African research station. Experimental Agriculture 30, 441–446.

Mearns, L.O., Mavromatis, T., Tsvetsinskaya, E., Hays, C., Easterling, W., 2001. Comparative responses of EPIC and CERES crop models to high and low spatial resolution climate change scenarios. Journal of Geophysical Research 104, 6623–6646.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1996. The effect of changes in daily and interannual climatic variability of CERES-Wheat: a sensitivity study. Climatic Change 32, 257–292.

Messina, C.C., Hansen, J.W., Hall, A.J., 1999. Land allocation conditioned on El Nino-Southern Oscillation phases in the Pampas of Argentina. Agricultural Systems 60, 197–212.

McClendon, R.W., Hoogenboom, G., Seigner, I., 1996. Optimal control and neural networks applied to peanut irrigation management. Transactions of the ASAE 39 (1), 275–279.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems 50, 255–271.

McCown, R.L., 2001. Learning to bridge the gap between science-based decision support and the practice of farming: evolution in paradigms of model-based research and intervention from design to dialogue. Australian Journal of Agricultural Research 52, 549–571.

Meira, S., Guevara, E., 1997. Application of SOYGRO in Argentina. In: Kropff, M.J., et al. (Eds.), Applications of System Approaches at the Field Level, v.2. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 235–242.

Meisner, C.A., Karnok, K.J., McCrimmon, J.N., 1991. Using crop models in a beginning crop science laboratory. Journal of Agronomic Education 20, 157–158.

Mishoe, J.W., Jones, J.W., Swaney, D.P., Wilkerson, G.G., 1984. Using crop and pest models for management applications. Agricultural Systems 15, 153–170.

Monteith, J.L., 1986. How do crops manipulate water supply and demand? Philosophical Transactions of the Royal Society London A 316, 245–259.

Moulin, A.P., Beckie, H.J., 1993. Evaluation of the CERES and EPIC models for predicting spring wheat grain yield over time. Canadian Journal Plant Sciences 73, 713–719.

Muchena, P., Iglesias, A., 1995. Vulnerability of maize yields to climate change in different farming sectors in Zimbabwe. In: Rosenzweig, C., Allen, L.H., Harper, L.A., Hollinger, S.E., Jones, J.W. (Eds.), Climate Change and Agriculture: Analysis of Potential International Impacts (ASA Special

Publication 59). American Society of Agronomy, Madison, Wisconsin, pp. 229–239.
Ortiz, R.A., 1998. Crop simulation models as an educational tool. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 383–388.
Pang, X.P., Gupta, S.C., Moncrief, J.F., Rosen, C.J., Cheng, H.H., 1998. Evaluation of nitrate leaching potential in Minnesota glacial outwash soils using the CERES-Maize model. Journal of Environmental Quality 27 (1), 75–85.
Penning de Vries, F.W.T., van Laar, H.H., 1982. Simulation of growth processes and the model BACROS. In: Penning de Vries, F.W.T., van Laar, H.H. (Eds.), Simulation of Plant Growth and Crop Production. PUDOC, Wageningen, The Netherlands, pp. 114–136.
Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5, 109–131.
Parton, W.J., Ojima, D.S., Cole, C.V., Schimel, D.S., 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Bryant, R.B., Arnold, R.W. (Eds.), Quantitative Modeling of Soil Forming Processes (Special Publication 39). SSSA, Madison, WI, pp. 147–167.
Paz, J.O., Batchelor, W.D., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L., 1998. Analysis of water stress effects causing spatial yield variability. Transactions of the ASAE 41, 1527–1534.
Paz, J.O., Batchelor, W.D., Babcock, B.A., Colvin, T.S., Logsdon, S.D., Kaspar, T.C., Karlen, D.L., 1999. Model-based technique to determine variable rate nitrogen for corn. Agricultural Systems 61, 69–75.
Paz, J.O., Batchelor, W.D., Tylka, G.L., Hartzler, R.G., 2001a. A modeling approach to quantifying the effects of spatial soybean yield limiting factors. Trans. ASAE 44 (5), 1329–1334.
Paz, J.O., Batchelor, W.D., Tylka, G.L., 2001b. Estimating potential economic return for variable rate management in soybeans. Trans. ASAE 44 (5), 1335–1341.
Pfeil, E.V., Hundertmark, W., Thies, F.D., Widmoser, P., 1992a. Calibration of the simulation model ‘Ceres Wheat’ under conditions of soils with shallow watertable and temperate climate. Part 1: limitations in the applicability of the original model and necessary modifications. Zeitschrift fuer Pflanzenernähr Bodenk 155, 323–326.
Pfeil, E.V., Hundertmark, W., Thies, F.D., Widmoser, P., 1992b. Calibration of the simulation model ‘Ceres Wheat’ under conditions of soils with shallow watertable and temperate climate. Part 2: verification of the modified model ‘Ceres Wheat’. Zeitschrift fuer Pflanzenernähr Bodenk 155, 327–331.
Phillips, J.G., Cane, M.A., Rosenzweig, C., 1998. ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe. Agricultural and Forest Meteorology 90, 39–50.
Pinnschmidt, H.O., Batchelor, W.D., Teng, P.S., 1995. Simulation of multiple species pest damage in rice using CERES-rice. Agricultural Systems 48, 193–222.
Piper, E.L., Boote, K.J., Jones, J.W., Grimm, S.S., 1996a. Comparison of two phenology models for predicting flowering and maturity date of soybean. Crop Science 36, 1606–1614.
Piper, E.L., Boote, K.J., Jones, J.W., 1998. Evaluation and improvement of crop models using regional cultivar trial data. Applied Engineering in Agriculture 14, 435–446.
Piper, E.L., Smit, M.A., Boote, K.J., Jones, J.W., 1996b. The role of daily minimum temperature in modulating the development rate to flowering in soybean. Field Crop Research 47, 211–220.
Pisani, du A., 1987. The CERES-MAIZE model as a potential tool for drought assessment in South Africa. Water SA 13 (3), 159–164.
Podesta, G., Letson, D., Messina, C.D., Royce, F., Ferreyra, R.A., Jones, J.W., Jones, J.W., Llovet, I., Grondona, M., O’Brien, J.J., 2002. Use of ENSO-related climate information in agricultural decision making in Argentina. Agricultural Systems (in press).
Porter, C., Jones, J.W., Braga, R., 2000. An approach for modular crop model development. International Consortium for Agricultural Systems Applications, 2440 Campus Rd., 527 Honolulu, HI 96822, pp. 13. Available from http://www.icasanet.org/modular/index.html.
Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100, 81–92.
Quemada, M., Cabrera, M.L., 1995. CERES-N model predictions of nitrogen mineralized from cover crop residues. Soil Science Society of American Journal 59, 1059–1065.
Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resources Research 17 (1), 182–190.
Richardson, C.W., 1985. Weather simulation for crop management models. Transactions of the ASAE 28 (5), 1602–1606.
Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8, 1204–1213.
Ritchie, J.T., 1993. Genetic specific data for crop modeling. In: Penning de Vries, F., Teng, P., Metselaar, K. (Eds.), Systems Approaches for Agricultural Development. Kluwer Academic Press, Boston, pp. 77–93.
Ritchie, J.T., 1998. Soil water balance and plant stress. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41–54.
Ritchie, J.T., Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: ARS Wheat Yield Project. ARS-38. Natl Tech Info Serv, Springfield, Missouri, pp. 159–175.
Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding

Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 79–98.

Rosenzweig, C., Tubiello, F.N., 1996. Effects of changes in minimum and maximum temperature on wheat yields in the central US—a simulation study. Agricultural and Forest Meteorology 80 (2–4), 215–230.

Rosenzweig, C., Allen, L.H., Jr., Jones, J.W., Tsuji, G.Y., Hildebrand, P. (Eds.), Climate Change and Agriculture: Analysis of Potential International impacts (ASA Special Publication No. 59). Amer. Soc. Agron.,, Madison, WI 1995, p. 382.

Royce, F.S., Jones, J.W., Hansen, J.W., 2002. Model-Based Optimization of Crop Management for Climate Forecast Applications. Trans. ASAE 44 (5), 1319–1327.

Ruiz-Nogueria, B., Boote, K.J., Sau, F., 2001. Calibration and use of CROPGRO-soybean model for improving soybean management under rainfed conditions. Agricultural Systems 68 (2), 151–173.

Saarikko, R.A., 2000. Applying a site based crop model to estimate regional yields under current and changed climates. Ecological Modelling 131 (2–3), 191–206.

Sadler, E.J., Gerwig, B.K., Evans, D.E., Busscher, W.J., Bauer, P.J., 2000. Sit-specific modeling of corn yield in the SE coastal plain. Agricultural Systems 64, 189–207.

Salam, M.U., Jones, J.W., Kobayashi, K., 2001. Predicting nursery growth and transplanting shock in rice. Experimental Agriculture 37, 65–81.

Sau, F., Boote, K.J., Ruiz-Nogueira, B., 1999. Evaluation and improvement of CROPGRO-soybean model for a cool environment in Galicia, northwest Spain. Field Crops Research 61, 273–291.

Savin, R., Satorre, E.H., Hall, A.J., Slafer, G.A., 1995. Assessing strategies for wheat cropping in the monsoonal climate of the Pampas using the CERES-Wheat simulation model. Field Crops Research 42, 81–91.

Scholberg, J.M.S., Boote, K.J., Jones, J.W., McNeal, B.L., 1997. Adaptation of the CROPGRO model to simulate the growth of field-grown tomato. In: Kropff, M.J., et al. (Eds.), Systems Approaches for Sustainable Agricultural Development: Applications of Systems Approaches at the Field Level. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 133–151.

Seidl, M.S., Batchelor, W.D., Fallick, J.B., Paz, J.O., 2001. GIS-crop model based decision support system to evaluate corn and soybean prescriptions. Applied Engineering in Agriculture 17 (5), 721–728.

Seligman, N.C., Van Keulen, H., 1981. PAPRAN: a simulation model of annual pasture production limited by rainfall and nitrogen. In: Frissel, M.J., Van Veen, J.A. (Eds.), Simulation of Nitrogen Behaviour of Soil–Plant Systems. Centrum voor Landbouwpublikaties en Landbouwdocumentatie (PUDOC), Wageningen, Netherlands, pp. 192–221.

Semenov, M.A., Wolf, J., Evans, L.G., Eckersten, H., Iglesias, A., 1996. Comparison of wheat simulation models under climate change. II. Application of climate change scenarios. Climate Research 7, 271–281.

Sexton, P.J., Batchelor, W.D., Boote, K.J., Shibles, R., 1998. Evaluation of CROPGRO for prediction of soybean nitrogen balance in a Midwestern environment. Transactions of the ASAE 41, 1543–1548.

Singh, K.K., Kumar, R., Mall, R.K., Rathore, L.S., Sanker, U., Gupta, B.R.D., 1999. Soybean (*Glycine max*) yield prediction from current and historical weather data using CROPGRO model. Indian Journal of Agricultural Sciences 69 (9), 639–643.

Singh, P., Boote, K.J., Virmani, S.M., 1994a. Evaluation of the groundnut model PNUTGRO for crop response to plant population and row spacing. Field Crops Research 39, 163–170.

Singh, P., Boote, K.J., Rao, Y.A., Iruthayaraj, M.R., Sheikh, A.M., Hundal, S.S., Narang, R.S., 1994b. Evaluation of the groundnut model PNUTGRO for crop response to water availability, sowing dates, and seasons. Field Crops Research 39, 147–162.

Singh, P., Alagarswamy, G., Hoogenboom, G., Pathak, P., Wani, S.P., Virmani, S.M., 1999a. Soybean–chickpea rotation on vetric inceptisols: 2. Long-term simulation of water balance and crop yields. Field Crops Research 63, 225–236.

Singh, P., Alagarswamy, G., Pathak, P., Wani, S.P., Hoogenboom, G., Virmani, S.M., 1999b. Soybean–chickpea rotation on vertic inceptisols: 1. Effect of soil depth and landform on light interception, water balance and crop yields. Field Crops Research 63, 211–224.

Singh, U., Godwin, D.C., 1990. Modelling the impact of climate change on agricultural production in the South Pacific. In: Hughes, P.J., McGregor, G. (Eds.), Global Warming-Related Effects on Agriculture and Human Health and Comfort in the South Pacific. South Pacific Regional Environment Programme, New Guinea, pp. 521–537.

Singh, U., Thornton, P.K., Saka, A.R., Dent, J.B., 1993. Maize modeling in Malawi: a tool for soil fertility research and development. In: Penning de Vries, F.W.T., et al. (Eds.), Systems Approaches for Agricultural Development. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 253–273.

Singh, P., Virmani, S.M., 1994. Modeling growth and yield of chickpea (*Cicer arietinum* L.). Field Crops Research 46, 1–29.

Singh, U., Matthews, R.B., Griffin, T.S., Ritchie, J.T., Hunt, L.A., Goenaga, R., 1998. Modeling growth and development of root and tuber crops. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 129–156.

Soil Conservations Service (SCS) 1972. National Engineering Handbook, Hydrology Section 4, Chapters 4–10.

Southworth, J., Randolph, J.C., Habeck, M., Doering, O.C., Pfeifer, R.A., Rao, D.G., Johnston, J.J., 2000. Consequences of future climate change and changing climate variability on maize yields on the midwestern United States. Agriculture Ecosystems and Environment 82, 139–158.

Steele, D.D., Stegman, E.C., Knighton, R.E., 2000. Irrigation management for corn in the northern Great Plains, USA. Irrigation Science 19, 107–114.

Swaney, D.P., Jones, J.W., Boggess, W.G., Wilkerson, G.G., Mishoe, J.W., 1983. Real-time irrigation decision analysis using simulation. Transactions of the ASAE 26, 562–568.

Thornton, P.K., Saka, A.R., Singh, U., Kumwenda, J.D.T., Brink, J.E., Dent, J.B., 1995. Application of a maize crop simulation model in the central region of Malawi. Experimental Agriculture 31, 213–226.

Thornton, P.K., Bowen, W.T., Ravelo, A.C., Wilkens, P.W., Farmer, G., Brock, J., Brink, J.E., 1997. Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. Agricultural and Forest Meteorology 83, 95–112.

Travasso, M.I., Magrin, G.O., 1998. Utility of CERES-Barley under Argentine conditions. Field Crops Research 57, 329–333.

Travasso, M.I., Caldiz, D.O., Saluzzo, J.A., 1996. Yield prediction using the substor-potato model under Argentinean conditions. Potato Research 39, 305–312.

Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), Decision Support System for Agrotechnology Transfer (DSSAT) Version 3. University of Hawaii, Honolulu, Hawaii 1994.

Tsuji, G.Y., 1998. Network management and information dissemination for agrotechnology transfer. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 367–381.

Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding options for agricultural production. Systems Approaches for Sustainable Agricultural Development. Kluwer Academic Publishers, Dordrecht, The Netherlands 1998, p. 400.

Tubiello, F.N., Rosenzweig, C., Volk, T., 1995. Interactions of CO_2 temperature and management practices: simulations with a modified version of CERES-Wheat. Agricultural Systems 49, 135–152.

Tubiello, F.N., Rosenzweig, C., Kimball, B.A., Pinter, P.J., Jr., Wall, G.W., Hunsaker, D.J., LaMorte, R.L., Garcia, R.L., 2001. Testing CERES-wheat with free-air carbon dioxide enrichment (FACE) experiment data: CO_2 and water interactions. Agronomy Journal 91, 247–255.

Uehara, G., 1989. Technology transfer in the tropics. Outlook Agricultural 18, 38–42.

Uehara, G., 1998. Synthesis. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options For Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 389–392.

Uehara, G., Tsuji, G.Y., 1998. Overview of IBSNAT. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options For Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 1–7.

Vos, de R.N., Mallett, J.B., 1987. Preliminary evaluation of two maize (*Zea mays* L.) growth-simulation models. South African Journal of Plant Soil 4 (3), 131–136.

Wafula, B.M., 1995. Applications of crop simulation in agricultural extension and research in Kenya. Agricultural Systems 49, 399–412.

Wagner-Riddle, C., Gillespie, T.J., Hunt, L.A., Swanton, C.J., 1997. Modeling a rye cover crop and subsequent soybean yield. Agronomy Journal 89, 208–218.

Welch, S.M., Jones, J.W., Brennan, M.W., Reeder, G., Jacobson, B.M., 2002. PCYield: Model-Based Decision Support for PRIVATE Soybean Production. Agricultural Systems 74 (1), 79–98.

White, J.W., Hoogenboom, G., 1996. Simulating effects of genes for physiological traits in a process-oriented crop model. Agronomy Journal 88, 416–422.

White, J.W., Hoogenboom, G., Jones, J.W., Boote, K.J., 1995. Evaluation of the dry bean model BEANGRO V1.01 for crop production research in a tropical environment. Experimental Agriculture 31, 241–254.

Wilkerson, G.G., Jones, J.W., Boote, K.J., Ingram, K.T., Mishoe, J.W., 1983. Modeling soybean growth for crop management. Transactions of the ASAE 26, 63–73.

Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationships between erosion and soil productivity. Transactions of the ASAE 27, 129–144.

Wolf, J., Evans, L.G., Semenov, M.A., Eckersten, H., Iglesias, A., 1996. Comparison of wheat simulation models under climate change. I. Model calibration and sensitivity analyses. Climate Research 7, 253–270.

Zalud, Z., Trnka, M., Dubrovsky, M., 2000. Change of spring barley production potential using crop model CERES-Barley. Rostlinna Vyroba 46 (9), 423–428.

Zalud, Z., Stralkova, R., Pokorny, E., Podesvova, J., 2001. Estimation of winter wheat nitrogen stress using the CERES crop model. Rostlinna Vyroba 47 (6), 253–259.