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CropSyst, a cropping systems simulation model

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Abstract

CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. CropSyst simulates the soil water and nitrogen budgets, crop growth and development, crop yield, residue production and decomposition, soil erosion by water, and salinity. The development of CropSyst started in the early 1990s, evolving to a suite of programs including a cropping systems simulator (CropSyst), a weather generator (ClimGen), GIS-CropSyst cooperator program (ArcCS), a watershed model (CropSyst Watershed), and several miscellaneous utility programs. CropSyst and associated programs can be downloaded free of charge over the Internet. One key feature of CropSyst is the implementation of a generic crop simulator that enables the simulation of both yearly and multi-year crops and crop rotations via a single set of parameters. Simulations can last a fraction of a year to hundreds of years. The model has been evaluated in many world locations by comparing model estimates to data collected in field experiments. CropSyst has been applied to perform risk and economic analyses of scenarios involving different cropping systems, management options, and soil and climatic conditions. An extensive list of references related to model development, evaluation, and application is provided.

Keywords: Farming systems; Agricultural modeling; Simulation models; Cropping systems; Watershed simulation; CropSyst; ClimGen

1. Introduction

CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. Emphasis has been placed on developing a user-friendly interface, providing links to GIS software, a weather generator, and other utility programs.

CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. These processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation

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water salinity, tillage operations, and residue management.

The development of CropSyst started in the early 1990s. The motivation for its development was based on the observation that there was a niche in the demand for cropping systems models, particularly those featuring crop rotation capabilities, which was not properly served. Efficient cooperation among researchers from several world locations, a free distribution policy, active cooperation of model developers and users in specific projects, and careful attention to software design from the onset allowed for rapid and cost-effective progress. Another important factor was the advantage of learning from a rich history of crop modeling efforts.

The first examples of crop growth models, mostly intended for use by the agriculture research community, were available during the 1970s (e.g. de Wit et al., 1970; Arkin et al., 1976). Applications oriented to management or field decision-making (irrigation scheduling, pest and disease control, etc.) appeared in the early 1980s (e.g. Wilkerson et al., 1983; Swaney et al., 1983). On-farm applications of models were also reported (e.g. Lindemann et al., 1987; McKinion et al., 1988). Models such as SUCROS and others associated with the 'School of de Wit' (Bouman et al., 1996) as well as those of the CERES (Ritchie et al., 1998) and CROPGRO (Boote et al., 1998) families of models had a significant impact on the crop modeling community.

For the analysis of cropping systems, the ability to simulate crop rotations is important. Models of the CROPGRO and CERES families, placed under the common umbrella of DSSAT (Jones et al., 1998) can be used in rotation configurations. However, the DSSAT approach has been slow in adopting a more generic simulation platform that would allow users to easily integrate these models and simulate crop rotations (Jones et al., 2001). The EPIC model (Williams et al., 1984) provides a simple but effective generic multi-crop simulation approach suitable for the analysis of crop rotations and cropping systems. However, the model has limitations due to the simplicity of its crop growth descriptions and related biophysical processes.

CropSyst was designed to draw from the conceptual strengths of EPIC, but including a more process-oriented approach to the simulation of crop growth and its interaction with management and the surrounding environment. In addition, a stronger emphasis on software design was a clear departure from the EPIC and DSSAT approaches. Attention to a balance between the incorporation of sound science in the models and the utilization of adequate software design practices has been a trait of CropSyst since the beginning of its development. In this regard, it shares somewhat common objectives with APSIM (McCown et al., 1996; Keating et al., 2003), a modeling approach that has evolved to place substantial resources in the development of quality software engineering practices.

2. CropSyst components and modeling approach

CropSyst is a suite of programs designed to work co-operatively, providing users with a set of tools to analyze the productivity and the environmental impact of crop rotations and cropping systems management at various temporal and spatial scales. The main components of the CropSyst Suite are: CropSyst parameter editor, a cropping systems simulator (CropSyst model), a weather generator (ClimGen), a GIS-CropSyst simulation co-operator (ArcCS), a watershed analysis tool (CropSyst Watershed), and several utility programs.

2.1. CropSyst parameter editor

The parameter editor serves as the main user interface to the CropSyst Suite package. The user interface provides editors for setting and modifying CropSyst parameters, running the model, and viewing the output. The various components and utilities can be selected or accessed from menus and buttons on the tool bar.

2.2. CropSyst

The cropping systems simulator is the core of the suite of programs. It contains all the necessary objects, procedures, and functions to simulate the productivity of crops and crop rotations in response to weather, soil and management. A description of the main processes in CropSyst is given in Section 3. The model simulates a *single land block fragment*. A land block fragment represents a biophysically homogeneous unit area with a uniform management regimen. Simulation scenarios for land block fragments are created by preparing parameter files describing the climate, soil, crops and crop management. A simulation control file identifies and links all the input files, provides initial conditions, selects optional simulation modules, and specifies the scenario to be simulated.

2.3. ClimGen

Long-term series of daily weather data are often required for the probabilistic analysis of weather-impacted systems (e.g. cropping systems management, hydrologic studies, environmental studies, and others). Weather generators are computer programs that use existing weather data to determine generation parameters, which in turn are used to generate long series of daily climatic data. The statistical properties of the generated data are expected to be similar to those of the actual data.

ClimGen is a weather generator that uses principles similar to those in WGEN (Richardson and Wright, 1984), but with significant modifications and additions. ClimGen generates precipitation, daily maximum and minimum temperature, solar radiation, air humidity, and wind speed. All generation parameters are calculated for each site of interest, allowing the program to be applied to any world location. Additional features allow users to estimate atmospheric vapor pressure deficit and solar radiation from existing temperature records. The performance of ClimGen has been evaluated in several studies (Stöckle et al., 1998; Acutis et al., 1998, 1999; Castellvi and Stöckle, 2002; Castellvi et al., 2002).

2.4. ArcCS

ArcCS facilitates GIS-based CropSyst simulation projects by using polygons derived from ARCVIEW or Arc/Info GIS. Each polygon represents a land block fragment. ArcCS uses the polygon attribute table produced by the GIS software to identify, generate and run a simulation scenario for each unique land block fragment. A new polygon attribute table of CropSyst output variables is generated, which can be used by Arc/Info or ARCVIEW to produce maps of the CropSyst outputs. Annual and harvest outputs are used in statistical analyses to produce output maps for the mean, coefficient of variation, and cumulative probability distributions for any of the variables selected by the user.

2.5. CropSyst watershed

CropSyst Watershed is an extension of CropSyst and ArcCS capabilities where land block fragments, defined as raster cells in a grid instead of polygons, are hydrologically connected. As in the ArcCS module, the watershed model will compose a simulation scenario for each grid cell. CropSyst Watershed uses ARCVIEW for Windows and its Spatial Analyst extension as geographical base. The Spatial Analyst for ARCVIEW allows users to define watershed boundaries and drainage network from digital elevation models data. In addition, it provides tools to rasterize and overlay polygon-based combination maps (produced by ArcCS) that represent unique combinations of soils, land use, management, and other characteristics within the watershed. CropSyst simulations are run for each cell, starting with the uppermost cells and continuing with lower elevations until the entire watershed is covered.

2.6. Miscellaneous utility programs

In addition to the main components, the CropSyst Suite package includes utility programs to estimate soil hydraulic parameters (Acutis and Donatelli, 2003) and global solar radiation (Donatelli et al., 2003), and for statistical comparisons of model estimates and measured data (Fila et al., 2003). It also includes a dynamic link library that can be integrated in other models to calculate reference crop evapotranspiration (Donatelli et al., 2002a).

3. Model description

The CropSyst model is intended for crop growth simulation over a single land block fragment with uniform soil, weather, crop rotation and management. Growth is described at the level of whole plant and organs. Integration is performed with daily time steps using the Euler's method. An overall description of the model follows.

3.1. Water budget

The water budget in the model includes precipitation, irrigation, runoff, interception, water infiltration, water redistribution in the soil profile, deep percolation, crop transpiration, and evaporation. Water redistribution in the soil can be simulated by a simple cascading approach or a numerical solution of the Richard's soil flow equation (Campbell, 1985; Ross and Bristow, 1990). Boundary conditions allow for flux or saturated upper boundary and for free drainage or saturated (water table) lower boundaries.

CropSyst offers two options to calculate reference crop ET (ET_0): the Penman–Monteith model (Monteith, 1965) and the Priestley–Taylor model (Priestley and Taylor, 1972). The implementation of the Penman–Monteith model follows the methodology suggested by FAO (Allen et al., 1998). This option requires daily maximum and minimum temperature, solar radiation, maximum and minimum relative humidity (or dew-point temperature), and wind speed. The Priestley–Taylor model only requires temperature and radiation data, but the user must provide an appropriate value of the Priestley–Taylor constant. ClimGen allows users to estimate daily solar radiation and humidity from temperature, and to generate daily wind data, provided that at least 2 years of complete daily records are available. Potential crop ET is determined by multiplying ET_0 by a crop coefficient (K_c). Ground coverage by the crop determines the partitioning into potential crop transpiration and potential soil evaporation. Actual transpiration and soil evaporation depend on water availability in the soil profile explored by roots and soil surface, respectively (Stöckle and Jara, 1998; Jara and Stöckle, 1999).

3.2. Nitrogen budget

The mineral N budget in CropSyst includes separate budgets for nitrate and ammonium. Processes include N transformations, ammonium sorption, symbiotic N fixation, crop N demand and crop N uptake. Nitrogen transformations (net mineralization, nitrification, and denitrification) and ammonium sorption follow the approach presented by Stöckle and Campbell (1989) while symbiotic N fixation is based on Bouniols et al. (1991).

Crop N uptake was modeled by adapting the approach presented by Godwin and Jones (1991), where N uptake is determined as the minimum of crop nitrogen demand and potential nitrogen uptake. Crop nitrogen demand is the amount of nitrogen the crop needs to meet growth requirements plus its deficiency demand. The deficiency demand is the difference between the crop maximum and actual nitrogen concentration.

The water and nitrogen budgets interact to produce a simulation of N transport within the soil. Other chemical budgets such as salinity also interact with the water balance. All balances are checked during a simulation, and errors are reported.

3.3. Crop phenology

The simulation of crop development is based on thermal time, which is the required daily accumulation of average air temperature above a base temperature and below a cutoff temperature to reach given growth stages. The accumulation of thermal time may be accelerated by water stress. This can be conceptualized as a response to increased crop temperature. Relations between air and crop temperatures for stressed and unstressed crops, expressed as a function of the vapor pressure deficit of the atmosphere, can be found in the infrared thermometry literature (e.g., Jackson, 1982).

When simulations for a particular crop or cultivar are conducted over contrasting locations or for a wide range of planting dates, thermal time alone may not be a good predictor of development. Vernalization and photoperiod requirements may need to be considered (Ritchie and NeSmith, 1991).

3.4. Biomass accumulation

Fig. 1 shows a flowchart describing the approach used in CropSyst to calculate daily biomass accumulation. The core of these calculations is the determination of unstressed (potential) biomass growth based on crop potential transpiration and on crop intercepted PAR. This potential growth is then corrected by water and nitrogen limitations, if any, to determine actual daily biomass gain.

Given the common pathway in leaves for carbon and vapor exchange, there is a conservative relationship between crop transpiration and biomass production. Thus, the potential daily biomass production can be calculated as (Tanner and Sinclair, 1983):

$$B_{PT} = \frac{K_{BT} T_P}{\mathrm{VPD}} \tag{1}$$

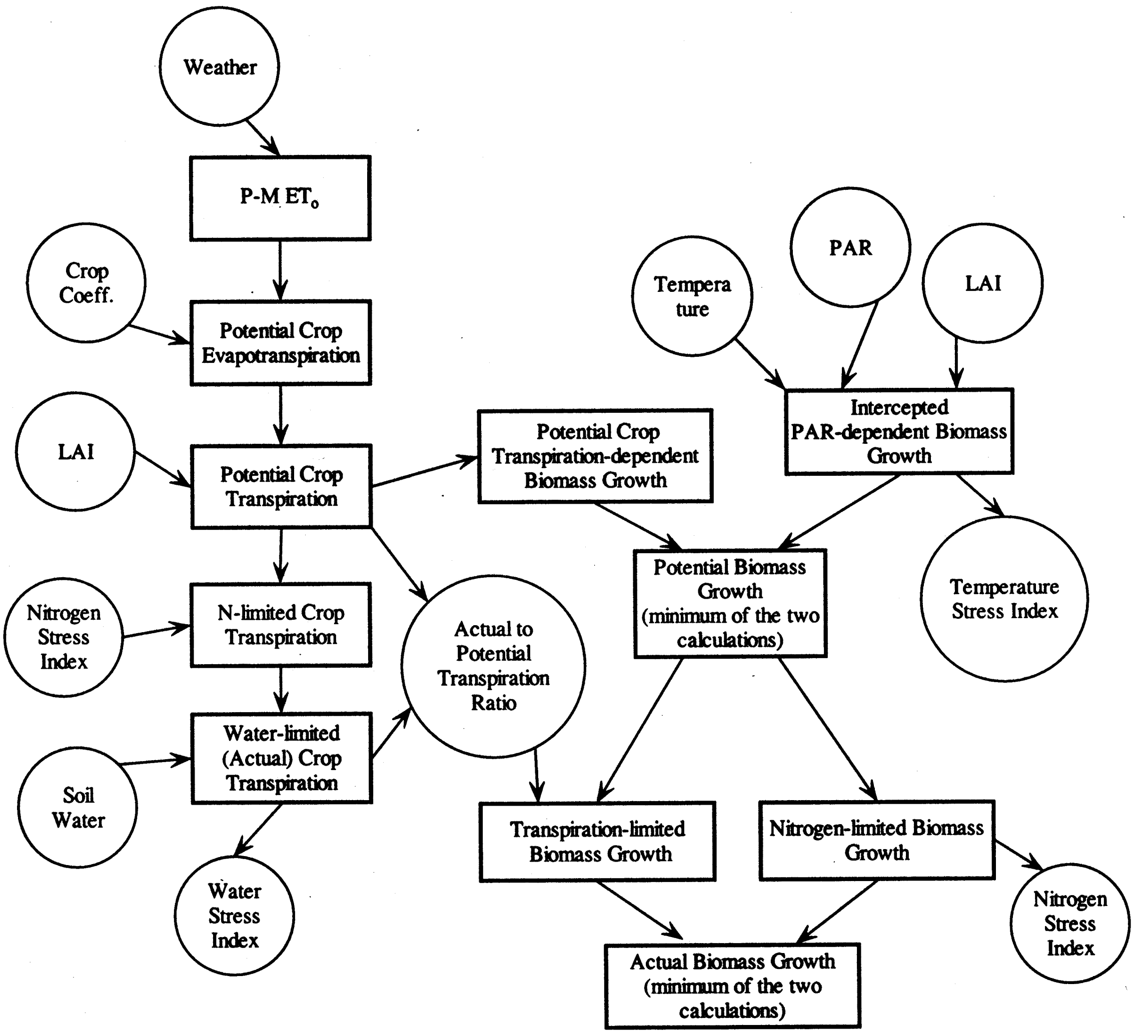

Fig. 1. Flowchart of biomass growth calculations in CropSyst.

where B_{PT} is the crop potential transpiration-dependent biomass production (kg m^{-2} day^{-1}), T_P is crop potential transpiration (kg m^{-2} day^{-1}), VPD is the daytime mean atmospheric vapor pressure deficit (kPa), and K_{BT} is a biomass-transpiration coefficient (kPa). Values for the latter parameter are available in the literature (Tanner and Sinclair, 1983; Loomis and Connors, 1992).

The Tanner–Sinclair relationship becomes unstable at low VPD values; in fact it would predict infinite growth at near zero VPD. To overcome this problem, a second estimate of unstressed biomass production is calculated following Monteith (1977):

$$B_{IPAR} = e\text{IPAR} \tag{2}$$

where B_{IPAR} is the intercepted PAR-dependent biomass production (kg m^{-2} day^{-1}), e is the radiation-use efficiency (kg MJ^{-1}) and IPAR is the daily amount of crop-intercepted photosynthetically active radiation (MJ m^{-2} day^{-1}).

Values for the parameter e in Eq. (2) are available in the literature (e.g. Kiniry et al., 1989). However, these values tend to present significant variability. For the approach implemented in CropSyst, it is important to select values from experiments with unstressed crops and conducted under low VPD environments. Although the parameter e includes the effect of the temperature regime prevailing during its experimental determination, temperature limitations during early growth are normally not accounted for. This may result in overprediction of biomass production during early growth at low temperature, particularly in the case of winter crops or early sown spring crops. A temperature limitation factor is included in CropSyst to correct the value of e during early growth, which is assumed to increase linearly (from 0 to 1) as air temperature fluctuates from the base temperature for development to an optimum temperature for early growth.

During each simulation day, the potential biomass production for the day (B_P) is taken as the minimum of B_{PT} and B_{IPAR}. This value is used as basis to calculate water and nitrogen-limited biomass growth (actual daily biomass production).

To determine water limitations, the effect of nitrogen deficiency on crop transpiration must be estimated. This effect is accounted for by increasing canopy resistance (Van Keulen and Seligman, 1987). For each simulation day, maximum (N_{max}), critical (N_{crit}), and minimum (N_{min}) plant nitrogen concentrations are calculated. N_{max} is the maximum attainable plant N concentration, N_{crit} is the critical plant N concentration (kg kg^{-1}) below which biomass growth is reduced, and N_{min} is the minimum plant nitrogen concentration (kg kg^{-1}) at which biomass growth stops. The values of N_{max}, N_{crit} and N_{min} fluctuate throughout the growing season as a function of accumulated biomass, following the concept of growth dilution (e.g., Greenwood et al., 1990). More details on this are given by Stöckle et al. (1997).

At plant N concentrations between N_{max} and N_{crit}, canopy resistance (r_c in day m^{-1}) remains unchanged (unstressed r_c value), but r_c increases at N concentrations between N_{crit} and N_{min} as follows:

$$r_{cNS} = \frac{r_c}{\left[1 - \dfrac{N_{crit} - N_c}{N_{crit} - N_{min}}\right]} \tag{3}$$

where r_{cNS} is N stressed canopy resistance (day m^{-1}), whose value is constrained to an arbitrary maximum representing canopy resistance with closed stomata, and N_c is the current plant nitrogen concentration (kg kg^{-1}). N-limited crop transpiration (T_N) is then calculated by reducing potential transpiration in response to changes in r_c.

$$T_N = T_P \frac{+\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_{cNS}/r_a)} \tag{4}$$

where Δ is the slope of the saturation vapor pressure function of temperature (kPa C^{-1}), γ is the psychrometric constant (kPa C^{-1}), and r_a is aerodynamic resistance to vapor transfer (day m^{-1}). See Allen et al. (1998) for more information on these parameters.

Water-limited or actual crop transpiration (T_A) is determined by the ability of the crop to uptake soil water to match the requirement set by T_N (which is equal to potential crop transpiration when N is not limiting). T_A is calculated as outlined by Stöckle and Jara (1998). Transpiration-limited biomass growth (B_T) is then given by:

$$B_T = B_P\left[\frac{T_A}{T_P}\right] \quad (5)$$

where B_T is in kg m^{-2} day^{-1}, B_P is the potential biomass growth for the day (kg m^{-2} day^{-1}), and T_A/T_P is the ratio of actual to potential transpiration.

Nitrogen-limited biomass growth (B_N) is calculated as follows:

$$B_N = B_T\left[1 - \frac{N_{crit} - N_c}{N_{crit} - N_{min}}\right] \quad (6)$$

where B_N is in kg m^{-2} day^{-1}. For plant N concentrations between the N_{max} and N_{crit}, biomass growth is not affected by the plant nitrogen status.

3.5. Leaf area development

The increase of leaf area during the vegetative period, expressed as leaf area per unit soil area (leaf area index, LAI), is calculated as a function of biomass accumulation:

$$\mathrm{LAI} = \frac{\mathrm{SLA}B}{1 + pB} \quad (7)$$

where LAI is in m^2 m^{-2}, B is accumulated aboveground biomass (kg m^{-2}), SLA is the specific leaf area (m^2 kg^{-1}), and p is a partition coefficient (m^2 kg^{-1}) controlling the fraction of biomass apportioned to leaves (a value of zero apportions all biomass to leaves).

The derivative of Eq. (7) with respect to biomass gives the change of LAI per unit change of biomass. Thus, the amount of new LAI produced in each simulation day is a function of the biomass production on that day. The end of the vegetative period marks the end of new LAI production. Leaf area duration, expressed in thermal time units (degree-days), is assigned to each unit of daily LAI produced. When a given daily LAI portion completes its duration, it is removed from current LAI, effectively simulating the process of leaf senescence. Water stress corrections are applied to both daily leaf area production and leaf area duration.

3.6. Root growth

Root growth in CropSyst is described in terms of root depth and root density, the latter calculated for each soil layer. Root depth is synchronized with leaf area growth, eventually reaching a specified maximum value (Rd_{max}) unless severe water or nitrogen limitations are present. Root density is assumed zero at a soil depth equal to the current root depth, and increases linearly to a maximum at a depth near the soil surface. The slope of this linear increase is given by the ratio of maximum root density to Rd_{max}. For shallow soils, only roots in actual soil layers extract water and nitrogen.

3.7. Yield

Yield simulation depends on total biomass accumulated at physiological maturity (B_{PM}) and the harvest index (HI = harvestable yield/aboveground biomass):

$$Y = B_{PM}\mathrm{HI} \quad (8)$$

where Y is yield (kg m^{-2}) and B_{PM} is also in kg m^{-2}. The harvest index is determined using as base an unstressed harvest index modified according to stress intensity (water and nitrogen) and crop sensitivity to stress during flowering and grain filling.

3.8. Crop growth response to elevated atmospheric CO_2

Two parameters in CropSyst define potential crop growth in response to water use and radiation capture: K_{BT} and e (Eqs. (1) and (2), respectively). In order to establish the effect of elevated atmospheric CO_2 on growth, values of these parameters under specified atmospheric CO_2 concentrations are required.

Determining the rate of change of these parameters in response to changes in CO_2 concentration requires complex carbon assimilation models that are not suitable for application at the cropping systems scale. Therefore, the implementation in CropSyst relies on experimental evidence of crop growth responses to CO_2. These experiments report the percent increase of growth under a specified atmospheric CO_2 concentration compared to growth at a baseline concentration. This information is processed using a modified version of the approach introduced by Stöckle et al. (1992).

3.9. Crop rotations

CropSyst simulations are performed using a daily time step within a period specified by start and ending dates. During this period, state variables such as residue biomass (surface and incorporated into the soil), evapotranspiration, soil water content, soil N content (nitrate and ammonium), soil organic matter and others are updated daily regardless if a growing crop is present or not (fallow). Crops and their corresponding management are initiated during this period according to a sequence given by a crop rotation template.

4. Data requirements

Five input data files are required to run CropSyst: Simulation Control, Location, Soil, Crop, and Management files. Separation of files allows for an easier link of CropSyst simulations with GIS software. Definitions, usage, and range of variation of all parameters required by CropSyst are given in the User's Manual (Stöckle and Nelson, 2000), and they are also available in the Help facility of the model interface.

The Simulation Control file combines the different types of input files as desired to produce specific simulation runs. It specifies the start and ending day of the simulation and the crop rotation to be simulated, and sets the values of all parameters requiring initialization. Also, inputs to this file allow users to switch on/off the simulation of soil erosion, soil salinity, nitrogen and CO_2 effects on crop growth, and to select soil water redistribution and runoff models.

The Location file includes information such as latitude, weather file code name and directories, rainfall intensity parameters, selection of ET models (Penman–Monteith or Priestley–Taylor) and associated parameters, and generalized information on wind for locations where daily wind data are not available.

The Soil file includes surface soil cation exchange capacity and pH for the estimation of ammonia volatilization, parameters for the SCS curve number approach (US Soil Conservation Service, 1972) for runoff calculation, and parameters for the Revised Soil Loss Equation (Renard et al., 1997) for erosion calculation. For each soil layer, thickness and texture must be specified. Based on this information, pedotransfer functions (Saxton et al., 1986) are used to calculate bulk density, volumetric water content at water potentials of −33 kPa (Field Capacity) and −1500 kPa (Wilting Point), and air entry potential and Campbell b value for the relationship between volumetric water content and water potential (Campbell, 1985). Whenever available, actual measurements instead of values estimated from texture can be used.

The Management file includes scheduled and automatic management events. Management events can be scheduled using actual date, relative date (relative to year of planting), or using synchronization with phenological events (e.g., number of days after flowering). Scheduled events include irrigation (application date, amount, and salinity concentration), nitrogen fertilization (application date, amount, source, and application mode), tillage operations, and residue management. The automatic event manager (irrigation and nitrogen fertilization) checks continuously the soil water and nitrogen content and it can be specified to provide management for maximum growth or to implement deficit strategies.

The Crop file allows users access to a common set of parameters to represent different crops and crop cultivars. This is a key feature of CropSyst. The file is structured in the following sections: phenology (thermal time requirements to reach specific growth stages), morphology (Maximum LAI, root depth, specific leaf area, leaf area duration, and other parameters defining canopy and root characteristics), growth (transpiration-biomass coefficient, radiation-use efficiency, stress response parameters, etc.), residue (decomposition and shading parameters for crop residues), Nitrogen (defining crop N demand and root uptake), harvest index (unstressed harvest index and stress sensitivity parameters), salinity tolerance, and CO_2-elevation response.

Crop parameters are the only input data that require calibration within a narrow range to properly represent specific crops and cultivars. However, those parameters defining the bulk of the crop response to the environment and management can be determined through field experiments. These parameters are the transpiration-biomass coefficient (Tanner and Sinclair, 1983), the radiation-use efficiency (Monteith, 1977), the specific leaf area, the stem/leaf partitioning coefficient, and the leaf area duration. In addition, thermal time requirements for different crop development stages can also be recorded from field observations. The basic experimental data set must include growing season evolution of biomass (leaves and stem), LAI, intercepted PAR, soil water, seasonal daily weather, total biomass at harvest and yield.

5. Software implementation and distribution policy

The model code is written in C++, and can be used on WINDOWS or UNIX-based platforms. An advanced user–friendly interface allows users to easily manipulate input files, verify input parameters for range errors and cross-compatibility, create simulations, execute single and batch run simulations, customize outputs, produce text and graphical reports, and link to spreadsheet programs. Simulations can be customized to invoke only those modules of interest for a particular application (e.g., erosion and nitrogen simulation can be disabled if not desired), producing more efficient runs and simplifying model parameterization. The model is fully documented (Stöckle and Nelson, 2000, last update), and the manual is also available as a help utility in the CropSyst interface. The CropSyst executable program, manual, tutorials, and utility programs can be retrieved free of charge directly over the internet at http://www.bsyse.wsu.edu/cropsyst or http://www.isci.it/tools. However, the source code is not distributed, eliminating the risk of ending up with many versions of the model.

5.1. Programming framework

CropSyst development has emphasized runtime performance using a conventional monolithic simulation engine approach incorporating all simulation elements in a single program at compile time. The normal object oriented features and coding conventions of the C++ language provide a straightforward and consistent simulation model development environment. New features and capabilities can be added and the overall logical framework of the model can be changed quickly.

Recent simulation model framework design efforts are attempting to develop a modular simulation engine with the primary goal of offering model developers and users the ability to augment an existing model or construct new models by plugging in modules at run time within a simulation development environment, sometimes allowing the modules to be written in a variety of programming languages. Often the modular design is an attempt to work around the software design and maintenance limitations of non-object oriented programming languages such as FORTRAN, C and dialects of BASIC. Such systems often require significant overhead in terms of both run time performance and coding to support modular model construction and data exchange protocols.

In CropSyst, modular programming is achieved by using C++ wrapper classes to encapsulate sub-models that can even be written in other programming languages. Many of the CropSyst sub-model objects are independent. The crop, soil, residue, evapotranspiration and weather objects can and have been used in other simulation models and programs. The entire cropping system model in CropSyst, itself being a C++ object class, can be used directly in other simulation models written in C++. Thus, CropSyst has been used as a sub-model in a regional scale land use optimization program (Rivington et al., 2001) and a whole farm simulation model (Chen et al., 2002).

5.2. User interface

One of the principles adopted early on was that the user interface would organize the parameters into data sets that could be pulled together to quickly produce new simulation runs via a simulation control file. Parameters are divided into location specific, crop specific, soil specific, and management parameters. One of the most fundamental aspects of the CropSyst structure is the mapping of input parameter values to user input screen representation to data storage files to simulation model objects in the program.

Simulation scenarios are constructed by selecting a soil and location and building crop rotations with sowing dates and an optional temporally dynamic management schedule associated with the crop. The scenario can also specify initial soil profile conditions, provide optional water table observations (to create an interpolated water table), and an optional schedule of soil profile recalibration data points.

5.3. Input file formats

For most parameter files, CropSyst uses a text file format similar to the Window INI file format. Parameters can be organized into sections allowing a logical structure that can more closely match the organization of parameters in the program. The format is extensible. New parameters can be added to the model, but allowing users to still use their old parameter files without modification. Adding new parameters requires modification of only a couple of lines of code and does not require reorganization of a database or utilities to reformat a database. Parameters not used by the model, additional data, and comments can be stored in the file even if not currently used by the model.

Recently, the code for reading parameter files has been further separated from the model's scientific code using a 'Data source/Data record' model, greatly reducing the amount of code required to read and write parameter files, and allowing the ability to store parameters in relational databases such as dBase and Oracle.

In addition to the parameter files, the only other input file is for weather data. The weather files consist of a simple space delimited text file table with daily weather values organized one day per line, one file per year. Four formats are currently recognized. Text files are easy to read and to generate from databases. However, they also have several disadvantages. To address these disadvantages, CropSyst now uses the 'Universal Environmental Database' (UED) binary file format for storing input weather data (as well as output results). This, coupled with an object oriented class for accessing the data, significantly reduces the size of the weather data files and improves runtime performance. The UED format also provides facilities for efficiently annotating the database with comments and unit specification.

5.4. Event driven modeling

To accommodate the dynamic nature of management practices in the simulation of long-term crop rotation scenarios, operations for both simulated management and simulation output options are presented to the model as dated events and/or operation modes. The simulation control parameters specify a list of sowing events and associated management event tables. These tables are loaded at runtime to build a dynamic event queue for all operations that occur during the simulation. Most objects are created dynamically in response to management operation events. For example a crop object will be created when a planting event is reached and will be disposed after harvest is processed.

Events can be set to occur on specific dates, dates relative to the planting date, or synchronized to the phenologic development of the crop or to the occurrence of specified conditions (e.g., automatic irrigation). Some events may propagate additional events that are added to the event queue; for example, a crop-planting event with an associated management file will add events for the management when the crop is planted. This flexibility allows CropSyst to be used in a predictive mode to model management practices based on crop conditions rather than fixed schedules.

All events can also be set to occur on specific dates. This allows CropSyst to be used in a calibrative mode to check the model against conditions that actually occurred either in actual farming scenarios or research studies. Fixed dates can either be set as actual dates, or relative to the year in the rotation, or set to occur every year on the same date.

6. Model testing and examples of applications

6.1. Evaluation of models and its limitations

Model evaluation is conventionally made by comparing simulation outputs with data collected from the 'real world' system represented by the model. However, such evaluations can be limited by several factors, making it somewhat difficult to establish the true performance of models. Detailed information on the initial conditions of the system is required to conduct these comparisons, information that it is not always available or is confounded by significant spatial variability under typical field situations. Model evaluation is increasingly difficult as the system under consideration becomes more complex, as is the case with crop rotations and cropping systems evaluated over several years. In such a case, many types of data are required to test the various processes simulated by the model. Furthermore, not all model outputs of interest can be evaluated because the corresponding measurements are difficult or unfeasible to obtain.

Another problem in model evaluation is the choice of quantitative indices used to evaluate model performance. These statistical indices normally rely on one-to-one (simulated vs. measured) comparisons, neglecting measurement errors and other sources of variation inherent to field experiments. Moreover, discrepancies between simulated and measured values in time series are not properly evaluated, greatly penalizing simulation outputs that have even a modest time shift with respect to measured data. Attempts to overcome some of these problems have been recently, proposed (Donatelli et al., 2002c).

6.2. Evaluation of CropSyst

The CropSyst model has been evaluated under a variety of conditions. By design, CropSyst only includes processes or relationships that are not site specific; indeed they are expected to work under most agricultural situations. However, several features of the model (e.g., organization of output variables, output handling, management events synchronization) have been modified or developed to facilitate these evaluations. The inclusion of processes such as salinity and water table effects, elevated CO_2 responses, and others have resulted from user–developer interactions prompted by model evaluations and applications. However, the basic algorithms for crop growth and development, and for simulating water and nitrogen balances have not been changed.

Examples of the performance of CropSyst in the simulation of biomass production and yield in response to water and nitrogen of single crops, over a single season and under experimental conditions are summarized in Tables 1 and 2. In these experiments, the treatments imposed provided a large array of conditions from dry to fully irrigated and from low soil available nitrogen to well supplied conditions. In these evaluations, the indicators of performance were the root mean square errors (RMSE), the ratio of RMSE to the observed mean (an indication of the relative magnitude of the error), and the Willmott index of agreement (d) that takes on values from 0 to 1.0, with an index of 1.0 indicating perfect agreement (Willmott, 1982).

Examples of model performance in the simulation of evapotranspiration are shown in Table 3. Jara and Stöckle (1999) conducted a more detailed evaluation of the simulation of crop water uptake. Simulated daily crop water uptake was compared with measurements of sap flow and soil water content for maize growing at Prosser, Washington, under a wet and a dry irrigation treatment, and with soil water content measurements for non-irrigated maize at Davis, California. For the wet treatment at Prosser, the RMSE for water uptake was 0.27–0.28 mm day^{-1} ($\sim$7% of the observed mean). For the dry treatment, the simulation accuracy decreased to a RMSE of 0.33–0.38

Table 1
Statistical comparisons of observed and simulated responses to water treatments for four crops and four locations (Stöckle et al., 1994, 1997)

Crop	Location		N	Obs mean (kg/ha)	Sim mean (kg/ha)	RMSE (kg/ha)	RMSE / Obs mean	d
Maize	Davis, CA and Ft Collins, CO	Grain yield	28	9831	9026	724	0.081	0.950
		Biomass	28	16 460	16 808	1246	0.076	0.954
	Auzeville, France	Grain yield	9	8026	7847	1707	0.213	0.963
		Biomass	9	19 038	18 358	2921	0.153	0.966
Wheat	Logan, UT	Grain yield	18	4100	4261	443	0.108	0.979
		Biomass	18	8033	8460	1121	0.140	0.961
Sorghum	Auzeville, France	Grain yield	8	7601	8055	896	0.118	0.967
		Biomass	8	16 684	17 358	1139	0.068	0.985
Soybean	Auzeville, France	Grain yield	9	2828	2804	381	0.135	0.970

N, number of data point; Obs, observed value; Sim, simulated value; RMSE, root mean square error; d, index of agreement.

mm day^{-1} ($\sim$9–10% of the observed mean). The time evolution of water uptake depicted well the measured sap flow. The RMSE for water content by soil layer ranged from 0.011 to 0.024 m^3 m^{-3} (5–9% of observed means) for Prosser and Davis experiments.

Simulations of N requirement and crop N uptake were evaluated using data collected at the Auzeville experiment station of INRA near Toulouse, France. These simulations resulted in a relationship between biomass at harvest and N uptake that correctly described an upper boundary (other limiting factors were not included in the simulations) for all observed data points. Detailed evaluation of biomass, leaf area, water uptake, and nitrogen uptake evolution throughout a complete growing season has also shown a reasonable performance of the model (e.g., Pala et al., 1996; Stöckle and Debaeke, 1997).

The capability of the model to simulate crop rotations was evaluated at sites in Northern and Southern Italy (Donatelli et al., 1996a). Simulated yields of different cropping systems were evaluated for seven consecutive years, generally showing good results with the exception of the simulation of summer crops following barley harvest (second

Table 2
Statistical comparisons of observed and simulated responses to water and nitrogen treatments for wheat at two locations (Stöckle et al., 1994; Pala et al., 1996)

Crop	Location		N	Obs mean (kg/ha)	Sim mean (kg/ha)	RMSE (kg/ha)	RMSE / Obs mean	d
Wheat	Logan, UT	Grain yield	30	4946	4963	383	0.077	0.975
		Biomass	30	10 293	10 339	786	0.076	0.996
Wheat (Cham 1)[a]	Northern Syria	Grain yield	16	2180	2410	550	0.250	0.920
		Biomass	16	7310	7090	870	0.120	0.960
Wheat (Hourani)[a]	Northern Syria	Grain yield	16	1750	2080	560	0.320	0.900
		Biomass	16	7190	7140	1030	0.140	0.920

N, number of data point; Obs, observed value; Sim, simulated value; RMSE, root mean square error; d, index of agreement.
[a] Cham 1 and Hourani correspond to improved and local varieties, respectively.

Table 3
Statistical comparisons of observed and simulated seasonal evapotranspiration for four crops and two locations (Stöckle et al., 1997; Pala et al., 1996)

Crop	Location	N	Obs mean (mm)	Sim mean (mm)	RMSE (mm)	RMSE/Obs mean	d
Wheat (Cham 1)[a]	Northern Syria	16	311	298	29	0.090	0.950
Wheat (Hourani)[a]		16	319	314	30	0.090	0.950
Sorghum	Auzeville, France	5	372	409	54	0.144	0.786
Soybean		6	412	443	42	0.102	0.956
Maize		6	416	414	13	0.031	0.997

N, number of data point; Obs, observed value; Sim, simulated value; RMSE, root mean square error; d, index of agreement.
[a] Cham 1 and Hourani correspond to improved and local varieties, respectively.

crops in the same growing season). A long-term 4-year rotation with different levels of mineral and organic fertilization was used to evaluate the model in Northern Italy (Berti et al., 2001). The results were satisfactory for the overall systems evaluated, and for winter wheat, maize, and sugar beet crops, whereas the simulation of soybeans was not satisfactory. In southeastern Australia, the model simulated well phenology, biomass, yield and water budget components of wheat, field pea and mustard (Diaz-Ambrona et al., 2001). An unpublished test by Diaz-Ambrona et al. also showed that the model simulated well the yield of farmer-grown wheat crops in the region between 1998 and 2000 (measured vs. simulated yield: $r^2 = 0.72$, RMSE = 0.21 μg ha^{-1}) (Sadras, 2002).

CropSyst performed well in simulating rice systems implemented in Northern Italy (Bocchi et al., 2001) with early varieties at high yield levels. In contrast, further work in model development appeared to be needed to simulate flooded rice. Simulations of spring and winter wheat water use and yields in wheat-fallow rotations at eastern Washington using different tillage and residue management practices over a period of 6 years showed that the statistical structure of simulated and field data was similar (Pannkuk et al., 1998). Simulated and field data also yielded similar water production functions. The RMSE fluctuated from 7 to 14% of the observed means for grain yield, and from 5 to 9% for evapotranspiration. The Willmott index of agreement fluctuated from 0.92 to 0.97, with all values but one equal to or better than 0.94. The water balance in CropSyst was evaluated for different cropping systems at a location in Southern Italy (Ventrella and Rinaldi, 1999), showing good overall model performance, except for estimates of soil water content at the end of the summer. Soil cracking was reported as the cause for overestimation of soil water content at upper soil layers and underestimation at lower soil layers.

The nitrogen balance in systems with inorganic and organic fertilization was evaluated on maize systems (Donatelli et al., 1996b), showing a good agreement for both soil water and nitrate estimates over time. Similar results, also for maize systems, were obtained in Central Italy (Silvestri et al., 1999). The application of CropSyst to intensive forage systems in Northern Italy (Confalonieri et al., 2001) was satisfactory in terms of alfalfa biomass estimates, but inadequate with reference to soil nitrogen estimates.

CropSyst was also evaluated in a comparative study with other models to evaluate nitrogen dynamics in Northern Germany (Richter et al., 1999). The results indicated that models more complex than CropSyst regarding the nitrogen module can better simulate soil nitrogen dynamics, although the difference among models in terms of fitting experimental data was small. Marchetti et al. (1997) extracted the denitrification module of CropSyst and compared simulation outputs with measured data and with outputs from other sub-models. The approach used in CropSyst resulted to be the most reliable among those tested.

CropSyst was evaluated for conditions with saline water table in Tunisia (Belhouchette et al., 2001). Simulation of crop growth limited by salinity compared well with experimental data, but the authors suggested that improvements were possible if fluctuations of the water table salt concentration over time could be specified as input to the model. Model evaluation using sprinkler line source experiments with different salinity and irrigation levels for barley grown at Zaragoza, Spain and corn at Davis, California and Fort Collins, Colorado was reported by Ferrer-Alegre and Stöckle (1999).

García de Cortázar et al., 2002 evaluated wheat straw decomposition rates under different temperature and moisture levels in two locations in Central Chile, comparing these measurements with simulations performed with CropSyst. The decomposition rate was evaluated for 3 amounts of wheat straw (3, 6 and 9 Mg ha^{-1}) and 6 temperature treatments (defined by the month when the straw was placed on the field). Comparisons of simulated and measured residues resulted in RMSE fluctuating from 0.24 to 0.29 Mg ha^{-1} (6–7% of the observed means), with the model providing a realistic simulation of the evolution of residue decomposition.

In summary, evaluations of CropSyst have shown that the model is suitable for the simulation of cropping systems in a variety of conditions, although some limitations have been reported. Properly calibrated (mainly to adjust cultivar specific crop parameters), and after some model verification is conducted (as recommended for all models), CropSyst can be a useful tool for the analysis of cropping systems. Users must exert caution when applying the model for conditions that are not currently simulated (e.g., cracking vertisols and fields impacted by pest and diseases). Examples of documented applications of CropSyst are presented in the next section.

6.3. Model application

Many applications of CropSyst, a deterministic model, have been done in a stochastic fashion by accounting probabilistically for weather variability. In these applications, model outputs are usually presented as probability distributions, allowing comparison of both the means and the variability resulting from simulated management practice scenarios. Using this methodology, CropSyst was linked to GIS software and applied to evaluate two levels of nitrogen fertilization on seven rotations implemented on a variety of soils in the Po Valley, Italy (Donatelli et al., 1999a; Meinke et al., 2001), allowing the estimation of drainage and nitrogen leaching resulting from different soil–weather–management scenarios. This study was also extended to a region in Central Italy (Donatelli et al., 1999b).

In Catalonia, Spain, CropSyst was used in conjunction with field experiments to develop a decision support system for nitrogen fertilization strategies (Ferrer-Alegre et al., 1999a). In the intensively irrigated Quincy-Pasco area of Central Washington State, a computer simulation study was conducted with the objective of estimating the amount and dynamics of nitrate leaching from a typical irrigated potato–winter wheat–maize rotation in this area (Peralta and Stöckle, 2001). In other studies, the model was applied to evaluate the impact of soil spatial variability on yield and N leaching (Marchetti et al., 1998; Bechini et al., 1999). Long-term simulations were also run using CropSyst to explore the performance of several cropping systems with different input levels (Morari et al., 2000).

CropSyst has been used to study the adaptation of crops to given regions. For example, CropSyst and ArcCS were applied to conduct an assessment of the adaptation of an improved cultivar of millet in Burkina Faso (Badini et al., 1997). The model was also used to evaluate different rotation options in Andorra (Ferrer-Alegre et al., 1999b). In a study in the US Pacific Northwest, CropSyst was used to assess the suitability of selected new crops for dryland farming in this region. The adaptation of yellow mustard, spring canola, spring pea, linola, hard red spring wheat, safflower, millet and maize to the climatic and soil conditions of this region was analyzed in terms of total productivity, yield stability, water use efficiency, and economics (Marcos et al., 1999; Marcos, 2000).

Coupling economic models with CropSyst allowed to perform a risk analysis of the interaction between rainfall and nitrogen fertilization of wheat in conditions of erratic water stress at three Australian locations (Sadras, 2002). The application of CropSyst coupled with an economic model was also illustrated in a case study in Turkey, aimed at evaluating various cropping systems (Eruygur, 2000). A multi-criteria analysis was run using CropSyst to provide technical indicators for an integrated evaluation of cropping systems (Mazzetto et al., 2001). The model is also used by the extension service of the Lumbardy region in Italy to produce a seasonal prediction of yield levels in four regions of the Po Valley. A bulletin is regularly updated and published on the web.

The impact of climate change scenarios on cropping systems has been studied using CropSyst and generated weather based on global circulation models at current atmospheric CO_2 concentration and at increased levels. Examples of this type of application have been reported by Tubiello et al. (2000) for Northern, Central, and Southern Italy, and by Bindi et al. (1999) for Southern Spain, Southern France, Northern Italy, and Greece. The response to climate change was also evaluated for sugar beet in various cropping systems implemented at six sites in Central and Northern Italy (Donatelli et al., 2002b), and for sunflower and wheat in Central Italy (Crisci et al., 2001). A study was conducted in the intensively irrigated agricultural area of Central Washington State to evaluate strategies for utilizing early climate forecasts in a region where climate fluctuations affect agriculture and complex water management institutions strongly govern adaptability to climate (Scott et al., 2001).

In summary, CropSyst has been widely applied to estimate the impact of climate, soils, and agricultural management on yield, water and nitrogen balance, drought adaptation, and other cropping systems issues at many world locations. Ongoing developments including CropSyst Watershed, precision agriculture capabilities, and a complete dairy farm production and nutrient management tool as well as plans to develop new farming system decision support tools will further broaden the scope of future applications of the model.

7. Closing the loop between development and application

Integration of users in the process of model evaluation and improvement has been important in the development of CropSyst. This feedback has helped to debug the code, to check model assumptions and the range of their validity, and to identify many features that have been introduced in the model. Frequent interaction with users has been and will continue to be a priority of the CropSyst development team. Fostering these interactions has required the development of a stable and user–friendly interface and model documentation, the introduction of a free distribution policy, the establishment of an internet page for model downloading and posting of information (with US and Italian sites) and an electronic bulletin board for all registered users, a concerted effort to timely solving problems posed by users (usually electronically), and offering training courses and maintaining visit exchanges with cooperators. All these activities have been instrumental in closing the loop between CropSyst development and application.

On the other hand, model development and applications would also benefit from a better communication and exchange of information among different modeling groups. The CropSyst development team believes that one important step to enhance the progress of cropping systems modeling and applications is to produce reusable, fully documented model components that can be readily utilized by other model developers and advanced users.

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