Crop Simulation Models as Tools in Computer Laboratory and Classroom-Based Education

Anil R. Graves, Tim Hess,* Robin B. Matthews, William Stephens, and Tabitha Middleton

ABSTRACT

Crop simulation models (CSMs) are mathematical, computer-based representations of crop growth and interaction with the environment. They play an important role in scientific research and resource management, and have been used to help students understand, observe, and experiment with crop systems. At the start of a new decade, it is timely that an assessment of these experiences in education is made. This paper synthesizes the positive and negative experiences in education to provide guidelines for using CSMs in computer laboratories and the classroom. Peer-reviewed literature, electronic media, personal experience and communications, and student perceptions were used to assess CSMs impact in education. Advantages for students are numerous. Advantages also exist for educational institutions. However, there are also disadvantages for students and educational institutions may struggle to use CSMs effectively. In general, CSMs should be used as an adjunct to, rather than as a substitute for other teaching methods. Instructors should maintain sufficient dialogue with students. Exercises developed for use with CSMs should encourage cognitive advances by the student. Visual appeal and clarity of CSMs should be ensured with standardized interfaces and graphical, dynamic representation of results. Input and output values should be in units appropriate to the topic of study or the country of use. Default values for parameters and online help, explaining the science behind the CSMs are important. The CSMs are valuable tools in education. However, they must be properly integrated into the teaching program and appropriately used by instructors.

CROP SIMULATION MODELS (CSMs) are "the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers" (Sinclair and Seligman, 1996). In essence, they are computer programs that mathematically simulate the growth of a crop in relation to its environment. They often operate at timesteps one or two orders of magnitude below the duration of the growing season and provide output data to describe attributes of the crop at different points in time (Matthews et al., 2000). Crop simulation models were first developed to run on mainframe computers in the 1960s (Bouman et al., 1996). Such models were used to estimate light interception and photosynthesis by crops (e.g., Loomis and Williams, 1963; de Wit, 1965). In the 1970s, the complexity of CSMs increased giving *comprehensive* models requiring large quantities of input data (Sinclair and Seligman, 1996). However, such complexity did not always lead to better models, as much of the behavior of a crop could be determined with a few key variables. In the 1980s *summary* models (Penning de Vries et al., 1989) and *parsimonious* models (e.g., ten Berge et al., 1997; Peiris and Thattil, 1998) were developed, although this was often with the aid of more complex models. Customized models also became more important with the realization that user-requirements often determined which should be used (Matthews et al., 2000). Awareness of the limitations of CSMs has increased since their introduction. These include the difficulty of providing input data, the stochastic nature of this input data in a temporally and spatially continuous environment (Burrough, 1989a, 1989b), and the difficulty of representing complex situations numerically (Passioura, 1973). Despite these difficulties, there is evidence that CSMs can play an important role in scientific research, decision support, and education (Matthews et al., 2000).

The potential use of computer simulations as educational tools was first investigated in the 1970s (Baker, 1978; Rushby, 1979). Thompson and Simpson (1973) describe the use of a *simulator program* written in FORTRAN IV using an IBM 360/65 computer at the Virginia Polytechnic Institute. Elsewhere, Peltz (1978) identified and documented a number of simulation models used for instruction in forestry. Simple computer simulations for farm management instruction also existed in the 1970s (Menz and Longworth, 1976; Solms, 1976). Our literature review revealed a paucity of published information on the use of CSMs in education (Matthews et al., 2000), and to our knowledge, it was not until 1981 that the first educational use of a CSM was made with the development of TRITIGRO 1 (McLaren and Craigon, 1981). More recently, the educational use of SPACTeach (Simmonds et al., 1995), PARCH (Fry, 1996; Stephens et al., 1996), PLANTMOD (Batchelor, 1997), SOYGRO (Ortiz, 1998), and Soil Water Balance (Jovanovic et al., 2000) have been described.

Current possibilities include making some CSMs available on the web. For example, the British Association for Information Technology in Agriculture (BAITA) (Heath, 1998) predicts continuous self-education with Computer Assisted Learning (CAL) software and web-based learning tools being the normal state of affairs for adults wishing to update their agricultural knowledge. In the UK, the Computers in Teaching Initiative (CTI)[1] promotes the use of computer tools in education through the web. The CTI Centre for Land Use and Environmental Science (CTI-CLUES)[2] provides a website for instructors wishing to find information on conferences, teaching advice, and resources on CAL.

Institute of Water and Environment, Cranfield Univ., Silsoe, Bedfordshire, MK45 4DT, United Kingdom. Received 11 June 2001. *Corresponding author (t.hess@cranfield.ac.uk).

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http://www.JNRLSE.org

[1] CTI support service website: http://www.st-and.ac.uk/ITS/CAL/projects/cti.html (verified 10 Apr. 2002).

[2] CLUES website: http://www.clues.abdn.ac.uk:8080/ (verified 10 Apr. 2002).

Abbreviations: CSMs, crop simulation models; BAITA, British Association for Information Technology in Agriculture; CAL, computer assisted learning; CTI, Computers in Teaching Initiative; CTI-CLUES, CTI Centre for Land Use and Environmental Science; SWB, Soil Water Balance; HND, Higher National Diploma; UNED, Universidad Estatal a Distancia; ISE, Interact Simulation Environment; NRSP, Natural Resources Systems Programme; DFID, United Kingdom's Department for International Development.

Important lessons can be synthesized from these sources to outline the positive and negative impacts of CSMs in education and to provide guidelines for their use. Personal experience, personal communication, and findings from the use of simulation models in other topic areas have also been used, where appropriate.

The CTI has suggested that "one of the best ways to promote deep conceptual understanding of the real world is through the investigation of simulation models" (Anonymous, 1996b). Such hypotheses are rarely tested statistically, and only a few studies have been carried out to quantify the impact of CSMs as an alternative to traditional teaching tools.

For example, a questionnaire survey of 40 final-year B.Sc. students by McLaren and Craigon (1981) showed that students felt their interaction with TRITIGRO I had been beneficial. About 80% felt they had gained more from it than they would have from an essay-type project. Questionnaire surveys of eight students by Jovanovic and Annandale (2000) and seven students by Jovanovic et al. (2000)—using Soil Water Balance (SWB) to teach irrigation scheduling and crop physiology—showed that students felt they had benefited from its use. This view was also held by groups of undergraduate and postgraduate students at Cranfield University who used the PARCH model (N.M.J. Crout et al., Univ. of Nottingham, unpublished data, 1997) with structured tutorial sessions to investigate crop growth and yield in highly variable environments.

For comparative studies on the impact of computer simulations on learning, it is necessary to look at literature outside that relating to CSMs. Coleman et al. (1998) compared two groups of randomly selected computer–engineering students, one learning through CAL applications and the other through traditional lectures. Their analysis showed there were no significant learning differences between the two approaches.

Edward (1996) compared the learning of two groups of students undertaking HND[3]/BSc engineering courses. One group used a conventional laboratory and the other a multimedia package, including a simulation model. No learning difference was found between the two groups. In a pharmaceutical company, Williams and Zahed (1996) compared staff trained using traditional lectures and those trained with self-taught computer modules. Again, no significant learning or *satisfaction* differences could be determined between the two groups, although interestingly, the self-taught CAL group retained significantly more information after 1 mo than the traditionally taught group. Forsythe and Archer (1997) found that psychology students rated the use of CAL tools positively, and that "those with weak academic backgrounds, who consistently used the technology, achieved higher test results than weak students who did not use the technology." Thus, evidence suggests that learning through computer simulations can be at least as effective as learning through traditional methods. However, there are positive and negative aspects to the use of CSMs as educational tools. These are outlined in the following sections.

BENEFITS OF CROP SIMULATION MODELS

Young and Heath (1991) observed that simulation models are the "most widely accepted approach to CAL, focusing on problem-based learning." Within the context of the present discussion, the emphasis is generally on the application of existing CSMs in the areas of *experimentation* and *observation*.

Benefits for Students

Time is a limited resource for many students. Yet a major constraint to conducting traditional field or laboratory experiments in the plant and agricultural sciences is the length of time that it takes to grow a crop. Therefore, while such experiments are common in research programs, they are less frequently incorporated into teaching programs. A model allows the rapid simulation of the complete growing period, or even the simulation of several seasons, allowing for a more effective use of learning time.

Field experiments are often confounded by uncontrollable and unpredictable environmental influences (e.g., weather, pests, and diseases), which can obscure the anticipated learning outcomes. However, the use of a simulation model allows these environmental factors to be controlled so the impact of the treatment can be isolated.

Students can control the environment and isolate the influences of input variables. This allows them to create and observe the impact of perturbed environments. Experiments that are impossible, expensive, or undesirable and unethical in real-life can be undertaken (Anonymous, 1996b). Simulations thus provide a safe environment in which to make real-world decisions allowing students to undertake tasks when it would otherwise not be safe (Pilkington and Parker-Jones, 1996).

The use of CSMs can allow students to focus more on learning and understanding the subject matter. For example, McAteer et al. (1996), assessing the use of simulated vs. *wet* laboratory experiments in the life sciences, found that students spent less time learning how to use the computer and software than on learning how to use instruments and equipment for real life experiments.

Certain obscure biophysical processes cannot be effectively observed in the laboratory or can only be observed using expensive equipment. A simulation model can demonstrate these processes and allow greater insight into cause and effect than would be possible in simple observational experiments.

Crop simulation models embody the expertise of scientists at the forefront of research, and document the experience gained in experiments (Boote et al., 1996). This can be transferred to students, sometimes from areas of the world not easily accessible to them. For example, PARCH simulates the growth and development of sorghum [*Sorghum bicolor* (L.) Moench], millet (*Panicum miliaceum* L.), and to a lesser extent, maize (*Zea mays* L.), in semiarid environments, giving students the possibility to observe and experiment with virtual crops from tropical areas.

Complex concepts and relationships in the crop sciences are more easily conveyed to students through CSMs than through traditional means. The driving force behind the development of SPACTeach as an educational tool, for example, was the difficulty encountered in conveying concepts to students with a "blackboard full of equations" (Simmonds et al., 1995). SPACTeach brought to life the complexity of water movement in the soil–plant–water continuum with a clear, dynamic, and graphical presentation of water content changes with depth in the soil.

[3] Higher National Diploma (a 2-yr practically based UK qualification).

Typical reductionist scientific approaches can fragment knowledge. However, for students, an understanding of how various disciplines interact and interrelate is increasingly important. For example, Jeger (1997) has noted that more than an understanding of hard facts is required for crop protection measures to be effective and Miller (1993) has suggested that agricultural and environmental issues are often trans-science at the decision-making and policy level. As CSMs "integrate discipline, knowledge, and relationships to produce a descriptive tool for application beyond the individual science discipline" (Boote et al., 1996), they have an important role to play.

Computer simulations can be used in the form of a game in which the students are required to find an optimum set of inputs to achieve a desired outcome (Anonymous, 1996b). In *gaming*, students often learn from their peers as the model becomes the focal point around which discussion takes place and experiences are shared (Burton, 1989; McLaren and Craigon, 1981).

Crop simulation models are frequently used in problem-based learning exercises where students can investigate a model as a substitute for the real world. Through w*hat-if?* scenarios (Batchelor, 1997) or by trial and error, students heuristically learn to predict the impact of changes in inputs on the final output, and gradually hone in on the optimum solution. McLaren and Craigon (1981) noted that the TRITIGRO I model could demonstrate the importance of strategic management to students in this way. For example, spending large amounts of money on the crop system did not necessarily deliver greater economic benefits. Targeted spending on key factors or at key crop growth stages could deliver greater financial benefits. Lessons in good crop management and economic rationality that might have taken months or years to learn in real life were demonstrated quickly with the model.

Distance and self-learning are increasing as on-the-job training becomes more important. Crop simulation models can be used to facilitate this process because such students are often unable to attend learning centers for practicals or laboratory experiments. Ortiz (1998) described how SOYGRO was successfully adapted by The School of Natural and Exact Sciences at the Universidad Estatal a Distancia (UNED) in Costa Rica for distance learning.

Benefits for Institutions

The benefits of CSMs to educational institutions are important. Crop simulation models can substitute for scarce instructor time. The use of CSMs as part of a CAL program may be used to redress decreasing staff/student ratios (Young and Heath, 1991) or to reduce contact time (McAteer et al., 1996). Releasing instructors from the more clerical aspects of teaching in this way, gives them more time for other important university activities (Jovanovic and Annandale, 2000).

Simulation models allow instructors to extend their students' experience, in a context of diminishing financial and physical resources (Anonymous, 1996a). For example, CSMs could to some extent substitute for multiple sets of experimental equipment or large areas of land on which to conduct experiments, if these are limited.

Simulation models provide a safe working environment and allow teaching institutions to avoid ethical difficulties. In the life sciences, McAteer et al. (1996) found simulation models useful as a way of avoiding experimentation on animals. In the crop sciences, CSMs could be used both to provide a safe working environment and avoid ethical difficulties, where, for example, experiments with very high applications of dangerous chemicals are conducted.

The high levels of technical skills required for difficult practical experimentation are not required for the use of CSMs (although familiarity with computers is important). This allows students to conduct experiments, which would otherwise necessitate intensive training by the institution. The ability to conduct experiments without training students to use equipment saves institutional resources. However, the institution would also need to decide how far this detracted from the quality of the education provided to students.

LIMITATIONS OF MODELS IN EDUCATION

Limitations for Students

Our personal experiences suggest that, as with any other instructional technique, careful planning and implementation are required with the use of CSMs. Much of the negative feedback from student learning through simulation models relates to difficulties with software or hardware failure. In a survey of student opinion in the life sciences, McAteer et al. (1996) found students unfavorably disposed to the idea of replacing wet labs entirely with computer simulations. Some stated they would feel "cheated," "disappointed," or "bored." Others expressed the need for "hands on experience" and physical contact with the subject of study.

Where *off the shelf* models are used, there is a danger that students may experiment beyond the model's intended numerical or geographical range and start to produce misleading results. A well-produced package should alert the user to this or, for example, constrain input values to acceptable levels and provide the appropriate documentation.

By using CSMs, students are separated from the real-world phenomenon that they are studying and this can leave them believing that the model is "reality" (Philip, 1991; Passioura, 1996). However, CSMs are simplified models of reality and students should be aware of this. Inappropriate or incorrect assumptions can be made in developing models; misleading results produced. McLaren and Craigon (1981) noted that TRITIGRO I was, to some extent, subjective and limited by the ideology and ability of the authors.

Excessive reliance on simulation models can lead to the loss of real-life experience with the "tools of the trade" (McAteer et al., 1996). While the use of models can make efficient use of the student's and the instructor's time, students still need to learn the practical skills required for the measurement and recording of data produced by scientific experimentation.

Limitations for Institutions

Good simulation models, suitable for educational purposes, are expensive to produce and the educational market is relatively small (Thomas and Neilson, 1995). Devotion of resources by educational institutions to software development is not always cost-effective. As a result, much of the educational software has been developed by programming amateurs and lacks a professional interface. It is worth noting that

Table 1. Summary of the benefits and limitations of crop simulation models (CSMs) used as tools in education.

Summary of benefits and limitations for students

Benefits
- Reduction in time required for *experimentation* and *observation*
- Increased control over environmental variability
- Provision of safe learning environment
- Provision of opportunity to undertake undesirable experiments
- Transferral of expert knowledge and research experience
- Elucidation of complex plant–environment mathematical descriptions
- Synthesis of fragmented knowledge
- Integration of different but associated topic areas
- Focus for peer experience
- Promotion of heuristic learning
- Facilitates distance education and *education at a distance*
- Gives greater control of learning to the student

Limitations
- Loss of field and laboratory skills
- Separation from the subject of study
- Development of belief that CSMs are reality
- Frustrating and boring
- Experimentation and *observation* outside model range

Summary of benefits and limitations for educational institutions

Benefits
- Substitute for laboratory and field resources
- Saves financial resources
- Replaces staff in certain teaching activities
- Provision of safe working environment
- Prevention of ethical problems in teaching

Limitations
- Higher than anticipated adaptation and development costs of models and associated teaching materials
- Higher than anticipated instructor time required for effective use of CSMs
- Higher than anticipated infrastructure requirements and costs
- Poor choice and variety of models suitable for education
- Difficulty of integrating CSMs in existing courses
- Difficulty of transferring CSMs adapted or developed for education from one institution to another

while computer simulations can appear to be a cost-effective alternative to laboratory equipment, the "real monetary cost is often concealed by accounting systems friendly to computing" and it is the "concealed nonmonetary cost which is troubling" (Philip, 1991).

There are significant support costs for using simulation models in education that go beyond the simple hardware and software costs. The level of instructor support required is often underestimated, and anticipated savings in staff time (and cost) may fail to materialize. The software needs to be supported by other teaching materials and these usually have to be produced locally to ensure relevance and compatibility with the course. The cost of instructor time in the production of supporting materials is often overlooked.

It usually is more cost-effective to use off-the-shelf models than to develop custom-made packages for in-house teaching, but such models may not fit local curricula or suit the teaching methods of the instructor. With traditional teaching methods, the instructor can refer the student to a range of textbooks, with different approaches and styles. The range of software relating to a particular subject, on the other hand, is usually more limited.

Educational software developed at one institution has often failed to transfer to other sites (Thomas and Neilson, 1995). Teaching staff at one institution may be reluctant to use courseware that has been developed elsewhere. This may be because instructors find it difficult to adapt and use computer simulations for specific purposes. Also, software may not be well-documented and instructors thus feel they have insufficient understanding of the model to: (i) verify its relevance and (ii) explain why particular results are generated. Acceptance is more likely if models are fully and explicitly documented and evaluated by an independent third party. A summary of the benefits and limitations of using CSMs in education is provided by Table 1.

GUIDELINES FOR THE USE OF CROP SIMULATION MODELS IN EDUCATION

The Need for Investment in Change

The use of CSMs in education can require substantial investment in shifting current teaching paradigms. Teaching methods and beliefs may need to evolve to make good use of CSMs. There may also be requirements for investment in computer facilities, for example, in developing countries. The use of CAL is often less widespread than might be expected. For example, organizational constraints and the nature of teachers' and students' work has constrained the development of CAL in U.S. public schools (Loveless, 1996). In the UK, Scott and Robinson (1996) concluded that the use of information technology in education involved not just a change of teaching resources, but also of teaching strategies and beliefs.

The Need for Supportive Instructors

Supportive instructors are essential in the use of CSMs and the most successful outcomes in education appear to be where models are fully integrated into the teaching program (Edward, 1996; McAteer et al., 1996). Introductory lectures and plenary sessions are useful (Anonymous, 1996a). Edward (1996) concluded that the effectiveness of simulated labs was greatly enhanced by the active engagement of the instructor. Thomas and Neilson (1995) suggested the instructor needs to be present to guide the students, prevent waste of time, help in critical evaluation, and prompt the formation and testing of hypotheses. Our own experience is that students learning entirely with CAL tools can find it frustrating when instructors dissociate themselves from the teaching process, assuming that the CSM will do the teaching. Thomas and Neilson (1995) describe a possible compromise in their Interact Simulation Environment (ISE), which aims to reduce the costs of using simulations and increase the ability of instructors to guide students, albeit at a distance. Instructors can integrate a simulation into an interactive environment with text, images, and audio, and distribute it on the Internet. As well as giving instructors flexibility in the way they present simulations to students, such an approach gives students the flexibility to access the material over the Internet, at a time and place of their own choosing.

Pilkington and Parker-Jones (1996) noted that a danger in using computer simulations is the setting of cognitively undemanding tasks. This can result in the tendency for students to manipulate screen objects without developing deeper insight into the principles that underlie the observed behavior of the model. They suggest that students should be led into cognitive conflict by tasks that require new knowledge. This forces students to change the way they interpret the world. The role of dialogue with peers, and more particularly with instructors, is vital. This allows students to follow a role model, externalizing modes of thinking and reasoning to internalize, and guide their own thinking.

More practical suggestions have been outlined by Jovanovic and Annandale (2000) and Jovanovic et al. (2000) from their use of SWB. Students are given a proper theoretical background to the processes illustrated by the model, before it is demonstrated and used. Well-developed assignments, linking what has been presented through traditional teaching materials and the CSM, can then help to increase the student's understanding of the issues involved. Further suggestions include using simple, separate modules to illustrate individual components of the resource system, such as infiltration, drainage, canopy interception, evaporation, or transpiration, before using the entire CSM (Jovanovic and Annandale, 2000). Each topic is covered theoretically, before the complexity and dynamic interaction of the resource system are illustrated with the full model.

Instructors might consider providing students with a synopsis of the more philosophical and wide ranging issues raised by the development of simulation models in general. To what extent are they useful as representations of our mental models of the world? To what extent should we believe what they tell us? When should mechanistic and when should functional models be used? Several authors have examined such issues (e.g., Philip, 1991; Baker, 1996; Boote et al., 1996; Monteith, 1996; Passioura, 1996; Sinclair and Seligman, 1996). Students would benefit from being familiar with these, not simply because such questions are interesting in themselves, but also because they will help students to use models appropriately in the future.

The Appropriate Mathematical Model

The division of CSMs into *mechanistic* and *functional* types (Passioura, 1996) can have implications for students. While mechanistic models tend to be process based and used in research, functional models may be based on simple allometric relationships and used as engineering tools where practical solutions are required. Understanding the strengths and weaknesses of either approach is important and will help students make critical and informed use of CSMs in their future careers.

The Appropriate Model Characteristics

Certain packaging features are generically important in education. A CSM should cater to a variety of different student levels, teaching approaches, and subject areas. Increasing the level of flexibility will often improve its usefulness to educational institutions (Thomas and Neilson, 1995).

The transparency of a model is important in education. Transparent models allow students to examine the structure and process of the models. This facilitates the process of learning (Sinclair and Seligman, 1996). For some models, this would mean that only the program source code can be examined. However, models developed in graphical modeling environments, such as Stella[4] or ModelMaker,[5] are inherently more transparent. Opaque *black-box models* that merely present a user interface are not subject to the depth of scrutiny that may be required for effective learning. The assumptions and logic of such models may be difficult to determine and the teaching impact can be reduced.

However, we suggest that this should not preclude the use of black-box models in education. These also have a useful role to play. For example, by observing the change in output for a given change in input, such models allow the student to develop simple heuristics that can be applied in other areas of their studies. For example, allowing a student to observe how crop yield changes as levels of water and fertilizer vary should lead to an understanding of the concepts of limiting resources and interaction, without necessarily requiring a full understanding of the science involved in water and nutrient dynamics.

The Appropriate Software Features

In our experience, students should find using the software clear, simple, intuitive, and flexible. Learning how to use the software should occur rapidly, so that the majority of the student's learning time can be devoted to the twin processes of understanding and experimentation. There have been examples where models developed for other purposes have been used in education and students have struggled with the interface. Students then start to mistakenly perceive that the objective of the exercise is to get the model to function. Singels (Agronomy Department, South African Sugar Association, personal communication, 2000) used the PUTU suite of models (de Jager et al., 1983) in crop-modeling courses and noted that students "struggled to master all the intricacies of the menus in the short time available…" In this situation, deeper lessons relating to understanding the system's behavior can become obscured.

Speed of program execution is an important characteristic of models to be used in education (Jovanovic and Annandale, 2000). If students cannot see the results within a few seconds (or exceptionally, within a few minutes), their attention (and hence the message) can be lost. Thus, relatively simple models, requiring few input variables, may be more appropriate for educational needs (Jovanovic and Annandale, 2000).

The use of inappropriate languages or symbols in the interface can be a great distraction to the student. Any language, symbol, or unit that is unfamiliar to the student will make it more difficult to achieve the underlying learning objective. For example, the DSSAT shell (Tsuji et al., 1994) was used to teach undergraduate students in Thailand. Difficulties stemmed from the software and documentation being in English, rather than in Thai (Jintrawet, Univ. of Chiang Mai, Thailand, personal communication, 2000).

Many potentially suitable packages are not used due to the wide variation in units and symbols used. Courseware developed using Imperial units may not be accepted in educational systems that have adopted the SI system. Between disciplines, preferences for units also differ. This can be overcome, for example, in the SPACTeach package (Simmonds et al., 1995), which gives the user the choice of working with soil water potentials in units of head, energy, or pressure, with all input and output in the chosen units.

In our experience, an intuitive, standardized interface will help students to focus on the learning outcomes. For example, the use of a standardized interface, such as Windows, should make the software more intuitive to the student, who may al-

[4] High Performance Systems Inc. USA: http://www.hps-inc.com/ (verified 11 Apr. 2002).

[5] ModelKinetix, Ltd: http://www.modelkinetix.com/ (verified 11 Apr. 2002).

Table 2. Summary of guidelines that will provide an effective framework for the use of crop simulation models (CSMs) as educational tools.

Guidelines for institutions
- Investment in new teaching strategies and beliefs is often required
- Investment in computer resources may be required

Guidelines for instructors
- Introductory lectures and plenary sessions providing background to CSMs including definition, history, major uses, and benefits and limitations of different mathematical approaches to simulation modeling
- Use of the CSM as a tool and not an instructor
- Active instructor engagement and participation during student use of CSMs
- Development of exercises and tasks that encourage cognitive change
- Development of exercises and tasks that encourage dialogue with peers
- Initial use of model to teach individual components of resource systems
- Full use of CSM once individual components have been explained and demonstrated
- Continued use of other teaching tools, where these are more effective or appropriate

Guidelines for useful model features
- Transparent models are usually the most useful in education
- Speed of program execution
- Default values for parameters
- Online help explaining: (i) the science behind the model, (ii) measurement techniques and instrumentation, (iii) derivation of parameter values, and (iv) explanation of mathematical formulae
- Appropriate symbols and units for topic of study
- Appropriate symbols and units for country of use
- Appropriate documentation and verification by independent third parties

Guidelines for useful software features
- Simple, clear, intuitive software
- Standardized presentation such as Windows
- Graphical and tabular presentation of results
- Error and range checking for input variables
- Ability to pause simulations
- Ability to interrogate the state of compartments within the model
- Ability to export graphs and tables so results can be used for further assignments

ready be familiar with other software in this format. There is now a generation of graphical shells being developed for old (but useful) Fortran models that handle the input and output in a user-friendly manner, but retain the integrity of the original code.

Further important interface features include error and range checking of input data. Default values for parameters will save time. Online help (and a user manual) that explains the science behind the model, the derivation of parameter values, the explanations for equations, and the methods of measurements (Jovanovic and Annandale, 2000) will facilitate learning. Visual appeal is also important in education and graphical (possibly dynamic) representation of results, with the ability to pause a simulation and interrogate the state of compartments within the model, are useful features. The ability to export results, whether these are tables or graphs, for use in further assignments is also important. Documentation describing how the model can be used for specific lessons will aid the instructor, while the provision of case studies and historical data will help the student (Jovanovic and Annandale, 2000). A framework of guidelines that may contribute toward the effective use of CSMs in education is provided in Table 2.

Model Building

Building CSMs provides students with an alternative to the use of existing CSMs. Model-building skills are potentially important for students intending to work with natural resource systems in the future. Such experience at university equips them with the ability to develop simple computer models, although complex modeling problems may still require the involvement of professional modelers.

The use of visual programming environments, such as ModelMaker and Stella, greatly simplifies the process of model construction. Students can draw their models on-screen, link and define mathematical relationships between components, run the model, and graph results without the need to learn programming code. The process normally involves setting a systems problem for the student. Gradually, they build up the complexity of the model by adding more components to their system. Ideally, this is done with the integrated use of other paper and electronic materials.

Building CSMs provides a basis for experiential learning. The major educational benefits derived from model-building stem from the participation of the student in the learning process and the development of modeling skills. Students also develop the skills required for a systems-thinking approach to problem solving. ModelMaker has been used to teach modeling principles and applications in environmental and agricultural sciences (Morison, 1995). Model-building is also a means of synthesising previous teaching and a useful way of wrapping-up a course (Balster et al., 2001).

Building models can provide insight into the complexity of relationships and interactions in natural systems more clearly than the use of existing CSMs. The extent and importance of these relationships become clearer as the students develop and experiment with the output from their own models. Gaps in scientific understanding can be demonstrated (Anonymous, 1996a). The difficulties inherent to modeling will also become obvious as students develop their own models. Such difficulties will help students to understand that existing CSMs are not perfect representations of reality, and that professionally developed CSMs may also be flawed in process or structure.

One of the main difficulties associated with integrating model-building in a course of study is the time required to develop satisfactory CSMs. Balster et al. (2001) found that the time commitment for both students and instructors was excessively high in an assignment that used Stella to model mini-poplar ecosystems at the University of Wisconsin.

CONCLUSION

Crop simulation models are just one group of tools available to instructors teaching life sciences and natural resource management courses. Using CSMs provides benefits to students, instructors, and institutions. The net effect of these can be to improve the learning experience of the students, facilitate the process of teaching for the instructors, and economize on expensive facilities for educational institutions. Such benefits are likely to increase as experience is gained in the use of CSMs in education. However, these benefits should not obscure the limitations of CSMs as educational tools, and CSMs are not a panacea for under-funded laboratories and field sites or for poorly prepared teaching. If used to support clearly defined learning outcomes, the potential of CSMs is substantial, particularly in allowing students to investigate phenomena and responses that do not fit within the time frame of their course.

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