Learning Crop Physiology from the Development of a Crop Simulation Model

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ABSTRACT

Crop simulation models are recognized for their heuristic value by many teachers and used as a representation of crop functioning in crop physiology and agronomy courses. The development of a model by the students is rarely used by teachers as a training tool, especially in undergraduate courses. Our objective was to create a practical learning exercise (PLE) where the students had to develop a crop development, biomass production, and water balance model to improve the acquisition of knowledge gained from crop physiology lectures. Pea (*Pisum sativum* L.) was chosen as an example, but the same type of model is available for many crops. This PLE (two sessions of 4 h each) was tested on 52 groups of 2 students during 3 yr. Student learning efficiency from the PLE was assessed with a survey of short questions asked at different times after the lecture and after the PLE. With the help of two teachers, all student groups successfully developed the model on a spreadsheet. They were able to complete a validation exercise and to use the model to test the impact of sowing date on yield potential of the crop and to quantify the soil water deficit experienced by the plant. The PLE improved the retention of knowledge from the lectures. Computer-assisted teaching also showed some limits. Improvements of the PLE have been proposed and are under investigation.

Development of crop models started during the 1960s with models of light interception and photosynthesis (Sinclair and Seligman, 1996). By the middle of the 1980s, complex crop models integrating plant development and assimilate partitioning were available for many crops (Whisler et al., 1986). Most of these models were developed to be used as decision-support tools for crop producers or advisers [for example, the GOSSYM model associated with the COMAX expert system for cotton (*Gossypium hirsutum* L.) crop management; McKinion et al., 1989]. Their potential as decision support tools for policy makers is well documented (Boote et al., 1996; Matthews et al., 1997).

Nevertheless, crop models have mainly been used as research tools that helped in the integration of knowledge on crop functioning, in the analysis of field experiments and in the evaluation of the impact of selection for a particular trait of the plant (Boote et al., 1996; Ney and Wery, 1998). They also proved their usefulness as teaching tools in agronomy (Waldren, 1984; Hart and Hanson, 1990) and plant physiology (Wullschleger et al., 1992), to show how plants react to environmental factors and cultural practices. For example, Khan et al. (1996) developed a dynamic simulation model of the water balance of the soil–plant system to illustrate how water influences crop production for a specific soil–climate combination. In agreement with Meisner et al. (1991), our experience with this type of teaching exercise (Wery et al., 1996) shows that the students recognize the illustrative value of crop models. This is true also for farmers who generally agree more on the heuristic value of crop models to aid in the interpretation of their crop behavior than on their efficiency as online decision aid (Sinclair and Seligman, 1996). The illustrative value of the models can be improved by software specifically developed to use the output of existing crop models for teaching purposes. For example, N-Show allows the students to create dynamic graphs of the N flows in the soil–plant system as they are simulated by the CERES-Maize (*Zea mays* L.) model (Cabrera, 1994).

Nevertheless these crop models should be used with caution in crop physiology courses. As pointed out by Passioura (1996), when the models were developed to assist in the decision making process, they were evaluated for their ability to solve practical questions and not to accurately represent the functioning of the crop. The most complex crop models may not be the best choice to illustrate a crop physiology course, because they are not necessarily closer to the truth (Sinclair and Seligman, 1996). For example, a simple model based on individual leaf development (Lecoeur et al., 1996) may give a better explanation of the complex *after-effect* of a short water stress, with limited effect on C assimilation but large effect on final plant leaf area (Lecoeur et al., 1995) than a complex crop model based on the daily regulation of leaf growth by C supply. The analysis of the mechanistic value of the model is an important prerequisite for the teacher because, as pointed out by Passioura (1996), the students tend to think that what they see on the computer screen is the truth.

These risks may be reduced when the students participate in the development of the model. As stated by Sinclair and Seligman (1996), the exercise of constructing a model can be more valuable than the model itself, because the modeling process forces logical, quantitative thinking about the variables and processes that influence the performance of the crop. These principles were used by Goudriaan and van Laar (1994) to develop an excellent textbook with exercices on the modeling of crop growth, using the equations of the SUCROS model (Spitters et al., 1989). Apart from the publications of these autors and others of the C.T. de Wit Graduate Scool in Wageningen, there are few examples in crop physiology teaching where the exercise was to build the model and not to use an existing software.

The objective of this study was to develop a set of practical learning exercises (PLE) where the students had to build and validate a crop model, before using it as a decision support system. These exercises were developed on pea (*Pisum*

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Abbreviations: PLE, practical learning exercise; F, flowering; BSF, beginning of seed filling; PM, physiological maturity; RIE, radiation interception efficiency; RUE, radiation use efficiency; ASW, available soil water; TTSW, total transpirable soil water; FTSW, fraction of transpirable soil water; CDD, cumulated degree days.

sativum L.) because we had validated submodels of water balance, plant growth, and development on independant field data on this crop from our research program. In addition, the indeterminate growth habit of the pea plant was also interesting for the illustration of the development of a plant from its individual phytomeres (Lecoeur et al., 1995). As recommended by Sinclair and Seligman (1996), the model, described in the Appendix, was "simple and transparent enough" to allow the students to understand the logic underlying its behavior. We evaluated the efficiency of the modeling exercise in the acquisition and persistence of knowledge previously brought to the students during the lectures. The overall objective was to improve the learning efficiency of our crop physiology course in a context of reduction of the time given to this discipline.

MATERIALS AND METHODS

Learning Objectives

The PLE and the associated course were designed for undergraduate students (3rd year of BSc in Agronomic Science) of Agro. Montpellier (National School for Engeneers in Agronomic Science). The course was based on 10 h of lectures on plant development (as a function of temperature and photoperiod), biomass production (as a function of solar radiation), C allocation in the plant, and yield determination. The effect of water deficit and heat stress on these processes was also discussed. For each process we presented successively the ecophysiological basis, the simulation principles, and examples of application to crop management. The major objective of the PLE was the acquisition of the knowledge presented during the lectures. We tried to achieve it with the development and the use of a crop simulation model by the students.

Model Description

Three simulation submodels developed by INRA on pea cv. Solara (Ney and Wery, 1998) were used for this study. Details on the information given to the students (equations and parameters) are presented in the Appendix. In some cases the equations were not provided but were replaced by a description of the simulation principle that the students had to transcribe into an equation.

Plant Ontogeny Submodel

A pea stem can be described as a succession of nearly identical units, called *phytomeres*, each one consisting of an internode, a leaf, and an axillary meristem (Lecoeur et al., 1995). This meristem produces an inflorescence (with generally two flowers) if the phytomere is initiated after the time of floral induction (Ney and Turc, 1993). The plant ontogeny submodel describes phytomere initiation by the apical meristem (Turc and Lecoeur, 1997), and their development, as a function of thermal time, until key-phenological stages: end of leaf expansion (Turc and Lecoeur, 1997), flowering (F), beginning of seed filling (BSF), and physiological maturity (PM) (Ney and Turc, 1993). Flowering of the first reproductive phytomere is a function of average temperature and photoperiod during the period of 400 cumulated degree days (CDD) following emergence (Truong and Duthion, 1993). The model does not simulate the end of the period of phytomeres production by the apical meristem, so the final number of reproductive phytomeres was given as a parameter. The period of determination of seed number at each phytomere is the period between initiation and BSF of this phytomere (Ney et al., 1993). For average individual seed weight, the corresponding stages are BSF and PM. At the plant level seed number is determined between the initiation of the first reproductive phytomere and BSF of the last reproductive phytomere. The corresponding stages for individual seed weight are BSF of the first reproductive phytomere and PM of the last reproductive phytomere (Ney and Turc, 1993).

Carbon Budget Submodel

Daily aboveground biomass production is calculated with a simple model of C budget (Appendix) adapted from a soybean [*Glycine max* (L.) Merr.] model (Sinclair, 1986). The daily amount of photosynthetically active solar radiation is multiplied by radiation interception efficiency (RIE) and radiation use efficiency (RUE) of the canopy. The RIE is a function of leaf area index (Eq. [A11]), itself calculated from planting density (Eq. [A12]) and the number of expanded leaves (Eq. [A13]). The RUE is a function of phenological stage (adapted from J. Lecoeur and B. Ney, 1999, unpublished).

Water Budget Submodel

Daily available soil water (ASW) in the root zone is calculated with a simple water budget model based on the difference between major water inputs and outputs in a reservoir (J. Lecoeur and J. Wery, 1996, unpublished). The size of this reservoir is proportional to the root depth, itself calculated as a linear function of thermal time. Inputs are rainfall (and eventually irrigation), ASW in the previous day, and gain of soil water resulting from daily root growth. Outputs are drainage (calculated as the excess of water above the maximum total transpirable soil water, TTSW) and crop transpiration calculated from Penman daily potential evaporation, a crop coefficient linked to phenological stages (Eq. [A18]) and a reduction coefficient based on soil water status (Eq. [A19]).

Input Variables

The input variables of these submodels are daily average air temperature, photoperiod, photosynthetically active solar radiation, rainfall, and Penman potential evaporation. Each group of two students received a set of meteorological data for 1 yr (1996) in one location (Montpellier, lat. 43°30′N) where the output variables of the ontogeny and of the biomass production submodels had been measured on a pea crop cv. Alex (J. Lecoeur, 1997, unpublished). Each group received the data set obtained for one sowing date (12 March, 27 March, 10 April, 13 May, or 1 June 1996). This data set was used for the exercise of model validation. A second set, restricted to input variables, was provided for another location (Vergeze) 40 km east of Montpellier and another year (between 1989 and 1994 depending on the group of students) to use the model as a decision support tool.

Learning Exercise

The PLE consisted of two sessions of 4 h each (3 h to make the calculations and 1 h to analyze the data and write a short report). Session 1 was based on the development of crop ontogeny and C budget submodels and their validation with experimental data. In Session 2 these models were used to analyze the effect of sowing date (mid-December compared with end of March) on yield potential. Then the students had to develop the water budget submodel, and use it to analyze the risk of drought stress for the pea crop having the highest yield potential (i.e., the earlier sowing date).

For each session 26 students were split into groups of two and assisted by two teachers during the whole duration of the exercise. To avoid any prerequisite of computer programming, the PLE was developed on Microsoft Excel 5. The students were previously trained to build a table and a *X–Y* graph. Hardware used was a computer network with Pentium 133 processor, 16 Mb Ram, no hard disk. The teachers had a portable computer connected to videoprojector to explain the PLE to all the students simultaneously and show tricks to solve technical problems during the exercise.

Evaluation of Learning Efficiency of the Practical Learning Exercise

Each session was replicated four times with different groups of students and the PLE was tested during 3 yr (1996–1998).

In addition to the observation of the students behavior during the exercises, the learning efficiency of the PLE for the acquisition of knowledge brought by lectures was assessed with a survey in 1996 and 1997. Each student had 5 min to give a rapid answer to the two following questions:

Q1: If you have to describe the development of the phytomeres of a plant on a *X–Y* graph, which variable do you use as *X* axis? Answer: Thermal time from plant emergence, in CDD.

Q2: Same question for *Y* axis. Answer: the number of phytomeres on the main stem.

In 1996 each question was asked at the beginning of the PLE, which was 20 d after the lecture. The questions were asked again, in a slightly different form, 7 d after the PLE and at the final examination, which was 75 d after the PLE. In 1997 questions were asked in the beginning of Session 1, which was 1, 7, or 10 d after the lecture, depending on the groups of students.

RESULTS AND DISCUSSION

Model Development and Use

At the end of Session 1 the students had to use the outputs of the crop ontogeny submodel to give a graphic description of the plant structure and development (Fig. 1). This graph brings two kinds of information, depending on the direction it is read (following the approach of Ney and Turc, 1993; Lecoeur et al., 1995; and Turc and Lecoeur, 1997). From *Y* axis to *X* axis, Fig. 1 gives the time (in degree days) when each phytomere was initiated by the apical meristem, when its leaf stopped its expansion, when its reproductive organs were at flowering (F), beginning of seed filling (BSF), or physiological maturity (PM). At the plant level, from *X* axis to *Y* axis, Fig. 1 gives, at a given time, the stage of development of each phytomere of the stem. For example, at the beginning of flowering (calculated with Eq. [A4] in Appendix), leaf of Phytomere 12 stopped its expansion and its flower was at anthesis, although Phytomere 21 was just initiated. This determined the position, in the plant cycle, of the periods of determination of seed number and average seed weight (as described in Materials and Methods). The comparison of simulated and measured data (Fig. 1) showed that the model was correctly simulating the beginning of flowering, the evolution of the number of leaves at end of expansion, and of the number of flowers. The weakness of the model was in the evolution of the number of phytomeres initiated. At this point of the PLE, the students had to realize that the model was initialy developed on cultivar Solara and that we were using it for another cultivar (Alex). Their expected reaction was to propose a new parametrization of Eq. [A2] (in Appendix): reduction of the intercept (b_1) and increase of the slope (a_1).

The C budget submodel correctly simulated the evolution of aboveground biomass during the crop cycle for an irrigated pea crop (Fig. 2a, for the example of sowing in March). The same conclusion was obtained by the students working with the other sowing dates (Fig. 2b), indicating that the model developed for cultivar Solara can be used on cultivar Alex with the same set of parameters.

These comparisons of simulated and measured data were not presented as a validation of the model because they were made only with data from one experiment, at the same location where the model was parametrized but different years and sowing dates. Nevertheless, it helped the students to realize that important agronomic variables can be simulated with simple mathematical models, using a small number of climatic variables and crop parameters. At the same time, the weakness of the model for one of the variables (number of initiated

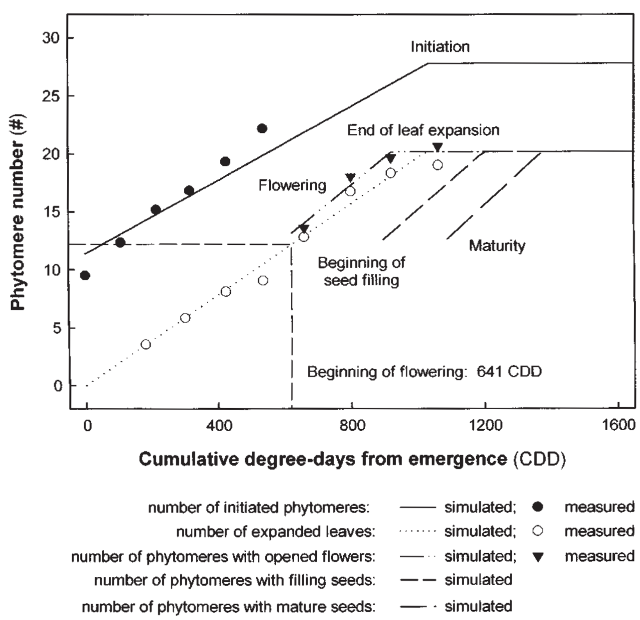

Fig. 1. Evolution of the number of phytomeres on the pea stem that have reached a given stage, as a function of thermal time. Comparison of simulated and measured values for a pea crop sowed at the end of March in Montpellier.

phytomeres) showed that some caution must be taken when using an incompletely parametrized model.

During Session 2 the students had to use the variables simulated by the C budget submodel to analyze the reduction of potential yield by late sowing: 5.0 t/ha for late-March sowing compared with 7.5 t/ha for mid-December sowing. They had to draw Fig. 3 where the solar energy resource (Fig. 3a) can be put in front of the efficiency of the crop canopy to intercept this energy (Fig. 3b) and to convert it into biomass (Fig. 3c). The late sown crop benefits from a higher incident radiation (average daily PAR of 10.6 MJ/m^2 instead of 7.2 MJ/m^2), but it has a shorter period of maximal RIE than the earlier sowing. Over the crop cycle, the amount of radiation intercepted by the canopy was reduced by 37% for the late sowing, thereby reducing its potential yield in comparison with early sowing.

At the end of Session 2, the students had to use the intermediate variable of the water budget model, FTSW (Fraction of Transpirable Soil Water) (Eq. [A17] in Appendix) to characterize the soil water deficit experienced by the crop (as suggested by Lecoeur and Sinclair, 1996; Lecoeur et al., 1996). As shown by these authors, below a FTSW of 0.5, stomatal conductance and leaf expansion of the pea plant are reduced as a function of FTSW, thereby reducing, respectively, RUE and RIE, in comparison with a well watered crop. This information, presented during the lecture, had to be used by the students to identify the periods of water deficit as those where FTSW was lower than 0.5. The superposition of these water deficit periods and the periods of yield component determination (Fig. 4) was used to identify if yield of unirrigated pea could be lower than the potential yield calculated with the C budget model. The synthesis of results obtained on the 6 yr by the various groups showed that every year the unirrigated pea crop would experience a long period of water deficit during the periods of seed number and seed weight determination, thereby reducing grain yield in comparison with the potential yield allowed by temperature and radiation. In 2 yr out of 6 yr (Fig. 3b) the water deficit was temporarily suppressed by the rainfall during May (around Day 120). These outputs from the model are in agreement with the evolution of soil water status measured in unirrigated pea crops at this location (S. Combaud and J. Wery, 1996, unpublished).

Learning Efficiency of the Exercise

All groups of two students were able to complete the PLE but they progressed at different rates during the session, depending on their skills in Microsoft Excel 5 manipulation

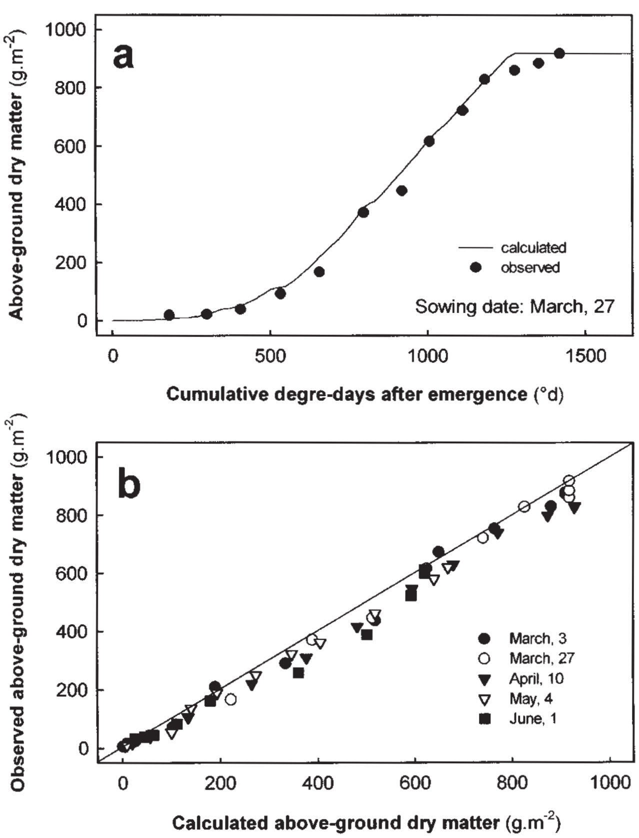

Fig. 2. (*a*) Simulated and measured accumulation of shoot biomass by a pea crop sown at the end of March in Montpellier. (*b*) Comparison of simulated and measured shoot biomass for five sowing dates (3 March, 27 March, 10 April, 3 May, and 1 June).

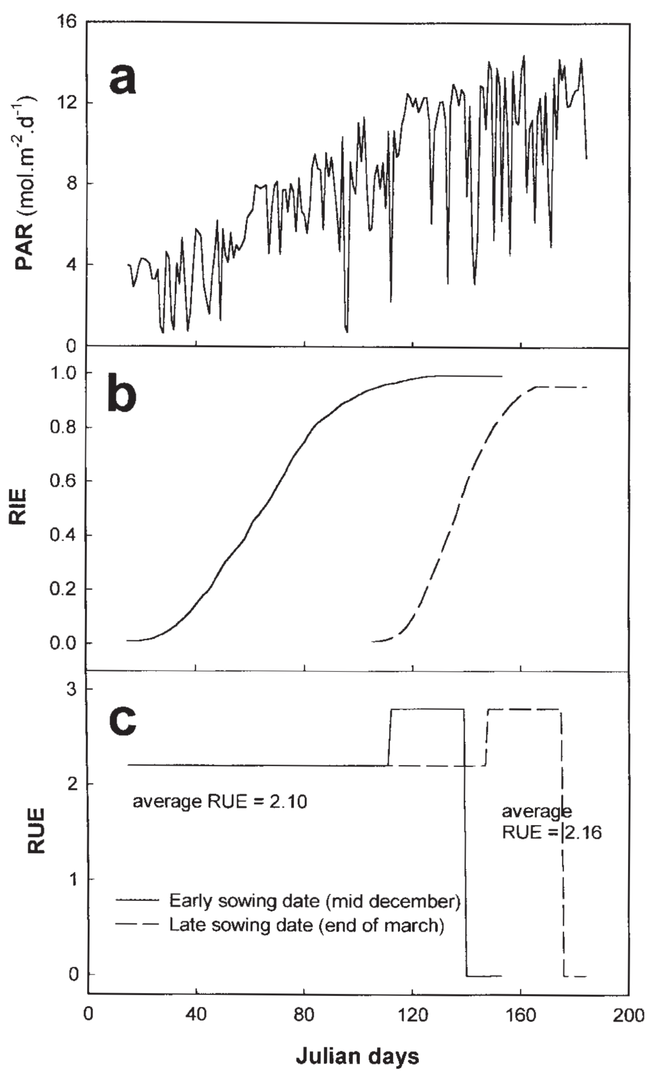

Fig. 3. Evolution during the crop cycle of (*a*, PAR) incident solar radiation, (*b*, RIE) simulated radiation interception efficiency, and (*c*, RUE) simulated radiation use efficiency by a pea crop sown at two contrasting dates in Vergeze.

and on their previous participation in the related lectures. This emphasizes the need for an individual tutorial adapted to each group, which required two teachers for 26 students. This makes the PLE a time-consuming activity for the teachers, in comparison with take-home exercises as those proposed by Goudriaan and van Laar (1994).

The questions asked of the students in the survey were based on important concepts in crop physiology such as thermal time (Question 1) and phytomere development (Question 2). The short time given to answer the questions (5 min) was chosen to test if this knowledge was inserted into the background of the students and to evaluate the contribution of the PLE to this acquisition of knowledge. Most of the students who attended the lecture gave the correct answer to Questions 1 and 2 (Fig. 5c and 5d) 1 d after the lecture. But this knowledge was rapidly lost by the students as shown by the reduction during 10 d of the percentage of correct answers for the two questions. When the PLE started 20 d after the lecture, correct answers were only 7% (for Question 1, Fig. 5a) and 16% (Question 2, Fig. 5b). The percentage of correct answers significantly rose again after the PLE, which is an indication of the efficiency of the manipulation of plant variables and equations in the acquisition of knowledge. The high levels of correct answers during the final examination (Fig. 5a and 5b) suggests that this acquisition of knowledge was sustainable. Comparison with a control group of students spending the same time with the teachers on other type of PLE, would give a more rigorous evaluation of the PLE. Nevertheless, it is was not possible in our teaching system, to apply parallel teaching approaches for undergraduate students.

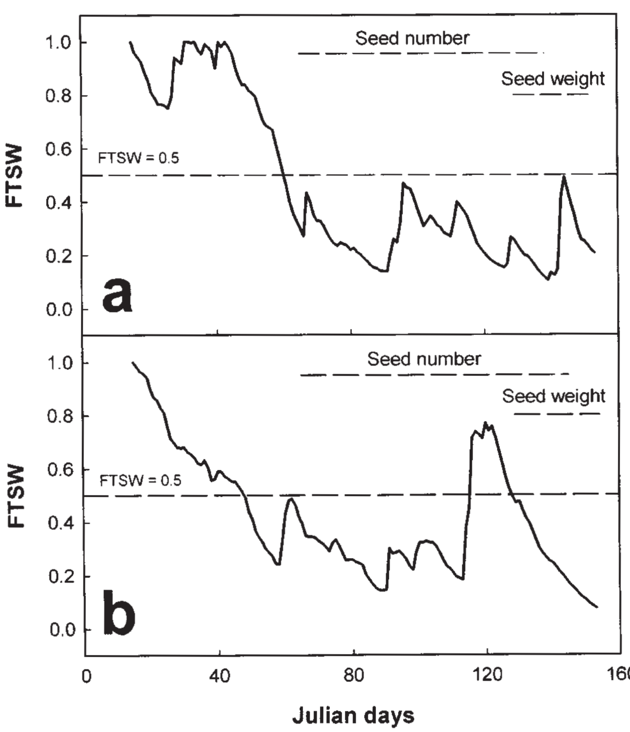

Fig. 4. Simulated evolution of the fraction of transpirable soil water (FTSW) during the plant cycle of a pea crop sown in mid-December in Vergeze during 6 yr. Patterns in Fig. a and b were observed, respectively, for 4 yr (1990, 1991, 1992, and 1994) and 2 yr (1989 and 1993).

Limits of Computer-Assisted Teaching

This study showed that a spreadsheet such as Microsoft Excel 5 allows the development of a dynamic simulation model by students with no expertise in computer programming. The major constraint was in the introduction of Eq. [A19] (Appendix), which represents the regulation of stomatal conductance by soil water status (Lecoeur and Sinclair, 1996). In the spreadsheet this equation yielded an insolvable circular reference between Eq. [A16], [A17], and [A19]. Nevertheless, this problem forced the students to understand the meaning of these equations and to realize that, with a daily timestep model, transpiration of a day can only be computed from soil water status of the previous day.

This study convinced us of the value of developing a computer simulation for a crop physiology learning exercise, as compared with only using a model, as already pointed out by many authors (Passioura, 1996; Sinclair and Seligman, 1996; Boote et al., 1996). This value arises from the fact that the students no longer see the computer as only a push button tool,

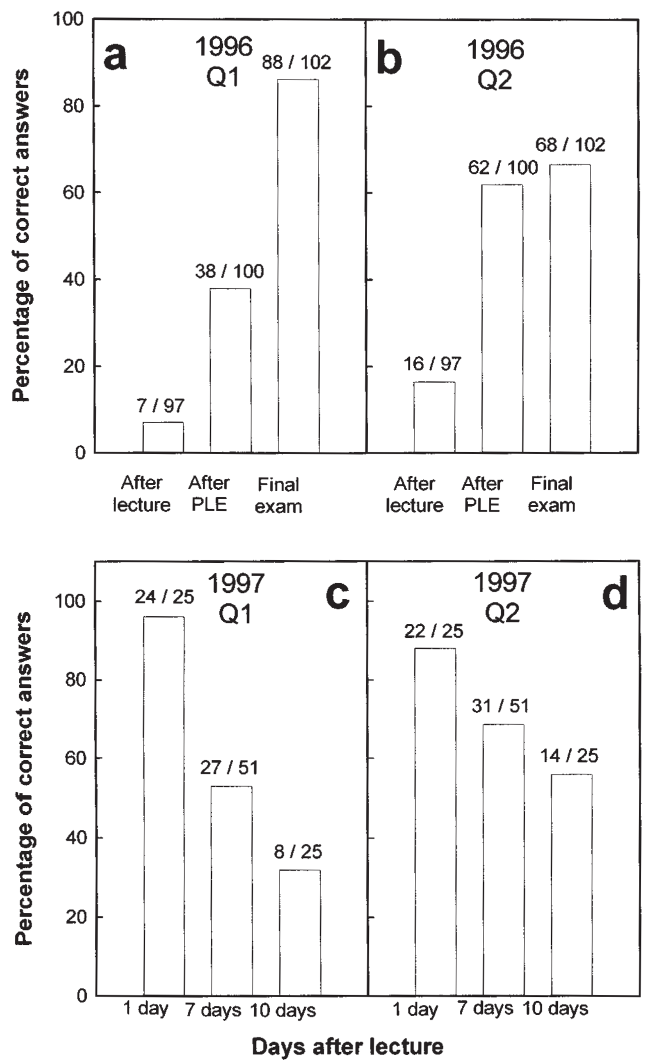

Fig. 5. Percentage of correct answers given by the students for Question 1 (*a*, in 1996 ; *c*, in 1997) and Question 2 (*b*, in 1996 ; *d*, in 1997) at different dates after the lecture and after the practical learning exercise (PLE).

but as an assistant in their thinking process. Learning is increased because they have to *read* the crop physiology knowledge contained in an equation (for example Eq. [A10] in the Appendix, which summarizes the concept of biomass production from light interception).

To help the students in their understanding of plant structure and development, two additional exercises are under investigation:

1. Development of a dynamic simulation of a 3-dimensional pea plant, using AmapSim, which can be used during the PLE to show the translation of Fig. 1 in a plant at any time of its growth cycle.
2. Addition of an experimental exercise before the PLE, where the students have to observe pea canopy, plant and apical buds, and describe them with the variables used in the simulations (leaf area index, number of expanded leaves, number of phytomeres initiated…).

CONCLUSION AND PERSPECTIVES

This study showed that the development of crop simulation models by the students is a useful complement of lectures in a crop physiology course, because it allows the manipulation and the integration of knowledge brought by the lectures. In addition, the use of these models during the PLE to address crop management option during a span of 6 yr provided a set of data familiar to the students, which we used in 1998 to summarize the course during a closing lecture. The results obtained during the 6 yr by the various groups were presented (see, for example, Fig. 4), discussed and used to remind the key issues of the course.

However, this PLE requires considerable time from the instructors and from the students. When less time is available, educationnal models such as PLANTMOD or WATERMOD (GreenHat Software, www.greenhat.com) offer an efficient alternative where the students can easily manipulate input variables and parameters and see their impact on water or C balance of a crop (Wery et al., 1996).

Some of the results of this study could be linked to the particular behavior or background of our French BSc students. Its application to other types of students could be useful for the improvement of the whole course, and we are open to collaboration with other teachers.

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APPENDIX

Description of the Information Given to the Students to Develop the Model

In this section, the relationships and parameters used for the model development are summarized.

Plant Ontogeny Submodel

Thermal time from emergence = CDD = Σ(Daily mean temperature − T_b), with a base temperature (T_b) of 0°C for pea (Ney and Turc, 1993) °d [A1]

Number of initiated leaves (NIL) = $a_1 \times$ CDD + b_1 [A2]

Number of expanded leaves (NEL) = $a_2 \times$ CDD + b_2 [A3]

where a_1, a_2, b_1, and b_2 are adapted from Turc and Lecoeur (1997).

CDD at flowering = $a_3 + b_3 \times$ (Mean temperature from emergence to CDD = 400°d) + $c_3 \times$ (Mean photoperiod from emergence to CDD = 400 °d) °d [A4]

where a_3, b_3, and c_3 are adapted from Truong and Duthion (1993)

CDDf = CDD − (CDD at flowering) °d [A5]

Number of phytomeres with flowers (NFP) = $a_4 \times$ CDDf + b_4 [A6]

Number of phytomeres with filling seeds (NSF) = $a_5 \times$ CDDf + b_5 [A7]

Number of phytomeres with seeds at physiological maturity (NPM) = $a_6 \times$ CDDf + b_6 [A8]

where a_4, a_5, a_6, b_4, b_5, and b_6 are adapted from Ney and Turc (1993). Specific crop parameters are date of emergence and final number of phytomeres with seeds.

Carbon Budget Submodel

Grain yield = (Aboveground biomass at physiological maturity) × HI [A9]

where harvest index (HI) is 0.5 for pea (J. Lecoeur, 1997, unpublished)

Daily aboveground biomass production = RIE × RUE × SR g m^{-2} [A10]

where RIE is radiation interception efficiency, RUE is radiation use efficiency, and SR is daily amount of photosyntheticaly active solar radiation (MJ); with RUE = 2.29 g MJ^{-1} from emergence to the beginning of flowering, 2.92 g MJ^{-1} from the beginning of flowering to 10 d after the end of flowering, and 0 after this stage. This evolution of RUE with phenological stages is a simplification of the experimental results obtained for a pea crop in our conditions (J. Lecoeur and B. Ney, 1999, unpublished).

RIE = 1 − exp(−0.6 × LAI) [A11]

where LAI is leaf area index.

LAI = Plant number × PLA [A12]

where PLA is plant leaf area.

PLA = $a_7 + b_7 \times$ NEL + $c_7 \times$ NEL^2 m^2 [A13]

where $a_7 = 0.22 \times 10^{-3}$, $b_7 = -0.06 \times 10^{-3}$, and $c_7 = 0.18 \times 10^{-3}$ (Lecoeur, 1997, personal communication, adapted from Sinclair, 1984).

Water Budget Submodel

Linear increase of root depth (RD) with CDD from emergence (when RD = 0.1 m) to end of flowering (when RD = 0.9 m). This sentence had to be translated by the student to:

Root depth (RD) = 0.1 + (0.8 × CDD)/CDDf m

The volumetric fraction of extractable water was fixed at 0.13, which is representative of many agricultural soils, except sands (Ratliff et al., 1983).

Total transpirable soil water (TTSW) = 0.13 × (RD) × 10^3 mm [A15]

Available soil water $(ASW)_i = ASW_{i-1} + [0.13 \times (RD_i - RD_{i-1})]$ + Rainfall − Soil and plant evaporation [A16]

The students had to realize that ASW could not reach a value higher than TTSW, the excess of water being assumed to be drained.

Fraction of transpirable soil water (FTSW) = ASW/TTSW [A17]

Daily potential evaporation (E_0) was provided from weather station.

Potential crop transpiration (E_p) = $k \times E_0$ mm [A18]

where k = 0.3 from emergence to 3 expanded leaves; 0.5 from 3 expanded leaves to 5 expanded leaves; 0.7 from 5 expanded leaves to 7 expanded leaves; 0.9 from 7 expanded leaves to 9 expanded leaves; 1.0 from 9 expanded leaves to the beginning of flowering; 1.2 from the beginning of flowering to 15 d after the end of flowering, and 1.0 from 15 d after the end of flowering to the plant physiological maturity.

The ratio between actual (E_a) and potential crop transpiration (E_p) is at 1 if FTSW is above 0.5, and it decreases linearly with FTSW below values of 0.5 (adapted from Lecoeur and Sinclair, 1996). The students had to realize that the definition of FTSW implies that this ratio is at 0 when FTSW = 0. Then the sentence can be translated in the following equation:

$E_a = E_p$ for FTSW ≥ 0.5

$E_a = 2 \times \text{FTSW} \times E_p$ for FTSW < 0.5 [A19]

The students had to realize that a hypothesis should be made for the soil water status on the first day of simulation (plant emergence). The expected assumption was that soil is at field capacity until the maximal rooting depth (0.9 m) because the pea crop is sown after a long period of rainfall on a bare soil.

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