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Software for Multiple Crop Production in Advanced Life Support Systems

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Abstract. *A Visual Basic™ software program, PACCS, was developed to aid NASA engineers plan, design, and operate biomass production components for Advanced Life Support Systems. PACCS integrates mathematical crop models of simulated controlled environment hydroponic production of wheat, soybean, and white potato with scheduling and analysis tools. Analysis options allow for studies on the feasibility of growing multiple crops in shared environmental zones and sensitivity of off-nominal environmental conditions on desired crop production schedules. A model-based predictive controller was included in PACCS to compensate for environmental disturbances in the production system.*

Keywords. computer software, model-based predictive control, crop modeling, NASA, Advanced Life Support

Introduction

NASA's Advanced Life Support Systems (ALSS) research program integrates biological systems with physical and chemical technologies. The idea is to develop regenerative life support independent of resupply of resources from earth (Henninger, 1989; MacElroy *et al.,* 1989; Eisenberg *et al.,* 1995). ALSS system components are commonly represented as 1) crew, 2) food processing and nutrition, 3) waste processing and resource recovery, and 4) biomass production.

The biomass production component is intended to provide necessary automation, environment, and cultural requirements for producing crops in controlled environment chambers in a microgravity environment. Eight to fourteen candidate crops were recommended by NASA nutritionists as necessary to satisfy crew nutritional needs on a vegetarian diet (Hoff *et al*., 1982). Example cereal, legume, and tuber/root crops include wheat, soybean, and white potato. If properly integrated with ALSS components, these plants may also regenerate the atmosphere, provide potable water, and recycle nutrients from hydroponics systems.

NASA has funded crop research in controlled environments over the past three decades. Most studies have focused on improving cultural systems and identifying environmental inputs which promote increased production of edible plant materials (e.g. Salisbury, 1991; Wheeler *et al.,* 1996). These findings have produced a large knowledge base on the production of several ALSS candidate crops in controlled environments with hydroponics systems.

Recently, NASA engineers have focused on construction of biomass production systems for earth-based ALSS testing facilities (Barta *et al.,* 1999). Questions remain, however, as to how to translate crop database information for engineering design purposes. Relevant planning, design, and operation issues such as the feasibility of growing multiple crops together under shared environments, defining required production areas for each crop based on mission requirements, and predicting and compensating for effects of long-term (> 24 h) disturbances on planned production schedules need to be investigated and addressed.

To provide support for these issues, one systems engineering task is to develop methods for extracting useful information from the crop knowledge base. Ideally, a computerized tool, similar to an expert system, in which all logical, heuristic, and functional representations of crop growth could be constructed for analysis of any production scenario (Fleisher and Ting, 2000). As the current state of engineering and biological knowledge is not available for such a task, system engineers develop simpler tools from which useful conclusions may still be drawn.

Objectives

The goal was to provide the ALSS community with a research methodology and software tool to address conceptual design, planning, and operational issues of an ALSS biomass production component. Engineering, mathematical modeling, control systems theory, and computer programming skills were integrated with plant biology to satisfy this goal. The result is demonstrated as the software program PACCS (Platform for ALSS Crop and Control Simulations). The program integrates mathematical crop models and control logic to study multiple crop production under shared environmental zones and sensitivity analysis of crop production schedules to nominal and off-nominal environmental conditions. The control algorithm was developed to compensate for effects of off-nominal disturbances on desired production schedules.

Materials & Methods

PACCS (Platform for Advanced life support Crops and Control Simulations) was developed using Visual Basic™ version 6.0 (Microsoft, Inc.) programming language. Multi-disciplinary research was conducted to establish a conceptual framework for the model as detailed in this section.

Crop Modeling and Experimentation

Explanatory DSSAT (Decision Support System for Agrotechnology Transfer) crop models (Tsuji *et al.,* 1994), verified to realistically predict crop behavior for certain environmental ranges, were obtained. These field agriculture models were previously modified for hydroponic plant production under elevated CO_2 concentration in controlled environments. Examples include a modified CROPGRO-soybean model (Cavazzoni *et al*., 1997) and a CERES-wheat model (Tubiello, 1995). A third model, the white potato model, SUBSTOR, was modified by Fleisher *et al*. (2000). Modifications for all three models included calibration of crop coefficients, accounting for differences between field and hydroponics controlled environment plant production, and implementing source code changes to photosynthesis and canopy light interception sub-models to account for high PAR (Photosynthetically Active Radiation) substrate albedo and increased diffuse light fraction observed in growth chambers. Each model was verified with relevant plant data from either NASA's Kennedy Space Center or literature.

Preparation of Crop Models

Although the modified-DSSAT crop models are well-suited to study direction and magnitude of changes in plant growth and development, they run on different platforms (MATHEMATICA and a DSSAT interface) and require time-consuming data-entry procedures to simulate off-nominal conditions. This makes it difficult to perform systems studies and analysis work and complicates construction of a model-based control algorithm. Multivariate polynomial regression (MPR) models were fit to simulated DSSAT input / output data to develop more portable models for each crop.

MPR (Vaccari and Levri, 1999) statistically relates a dependent variable with multiple independent variables, including non-linear and interaction terms. Six 2^{nd} order MPR models were constructed for each crop based on DSSAT simulated time-series data. For three of these models, the dependent variable was the relative growth rate in plant dry mass for 1) vegetative growth, 2) yield growth, and 3) total biomass growth following the initiation of yield organs. A fourth model was used to simulate the initial dry mass of yield organs. Two additional models predicted developmental dates for the formation of yield bearing organs and plant maturity. Independent variables for all six models included the average light intensity (photosynthetic photon flux, PPF), air temperature, and CO_2 concentration at the given time increment. A fourth independent variable, a 1^{st}-order lagged value for plant dry mass, was also included for the four MPR models which predict plant mass. A 24-hour time increment was used for model simulation. MPR model results were verified with the DSSAT model data for accuracy.

Model-based Predictive Control

Traditional control for controlled environment plant production maintains pre-determined environmental setpoints. Thus, environmental disturbances and their effects on the plant are not directly incorporated into the control. Newer approaches address this deficiency somewhat. For example, optimization is frequently used in greenhouse control to dynamically change setpoints based on changes in crop growth, market forecasts, and weather (Challa and van Straten, 1993). A similar approach was taken in developing a control algorithm for plant production in ALSS.

In model-based predictive control (Clarke, 1994), an observer, or mathematical model, is used to compute a state estimate of the process to be controlled at each time increment given values for the control input and measurement of the system response. The state estimate is fed into an 'optimizer' routine. The optimizer uses a model of the system to forecast future behavior as a function of current control inputs. A cost function, based on the squared error difference between a series of reference signals and forecasted system behavior and a weight on control effort at each time-step, is then minimized with respect to the control inputs using an optimization routine. The net effect is a new set of control inputs to be applied at the following time increment. The entire process is subsequently repeated at the following time increment.

In this application, MPR crop models were used to estimate the crop state at each time increment with simulated control values and as the forward model in the optimizer routine. The control seeks to eliminate differences between desired crop production (growth mass at each time step) and the simulated production given environmental disturbances. More detail is given in Fleisher and Ting (2001).

Results

PACCS allows study of multiple crop production (wheat, soybean, and/or white potato) under nominal and off-nominal environments (PPF, T, CO_2 only), and simulates effects of environmental input disturbances on growth and development. A general procedure for using PACCS is as follows. First, the user selects the current crop mix, consisting of either an individual crop or multiple crops sharing the same environmental zone. Then the user selects different simulation options. Options include a yield optimization routine, a growth production scheduling sensitivity tool, and application of control logic for crop production.

There are four main menus in PACCS, 'Files', 'Crop Mix', 'Simulations', and 'Results'. Rather than hardwiring model coefficients in the source code, PACCS uses a set of external files that provides the software with a list of variables and coefficients used in each MPR crop model. Thus, a total of 18 MPR files (6 per crop) are required to run the program. The 'Files' menu provides an interface for the user to specify the location (or path) of each of these files. The illustration (Figure 1) shows how the interface can be used to specify where a particular file is located on the hard drive if moved from its default location. To change the location of a file for a particular crop, the MPR crop model is selected first as shown in Step 3. The current path of the file appears on the bottom of the interface. The user can then select the new location of the file as shown in Step 4. The 'Change File' button must be clicked to save the new location in PACCS.

Selecting the 'Crop Mix' menu brings up a dialogue box (not shown). This allows the user to select any combination of wheat, soybean, and white potato for the simulation. If no crop is selected, PACCS uses wheat by default.

The 'Simulations' menu gives the user access to different types of simulations. The first, called 'Scheduling', provides access to a yield optimization routine. There are three sub-menus available to the user in this routine. The first, 'Inputs', opens up an 'Environmental Constraints' interface in which maximum and minimum environmental constraints may be input (Figure 2).

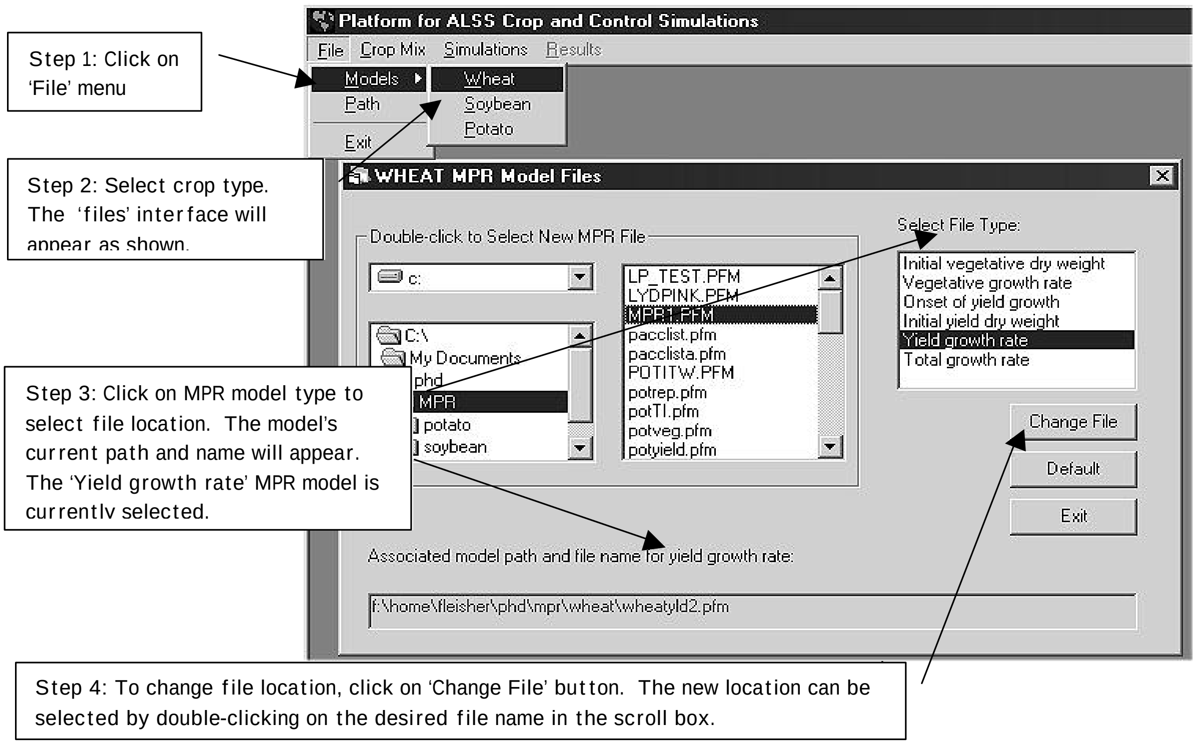

Figure 1: 'Files' interface with an example of selecting a new wheat yield growth rate MPR file.

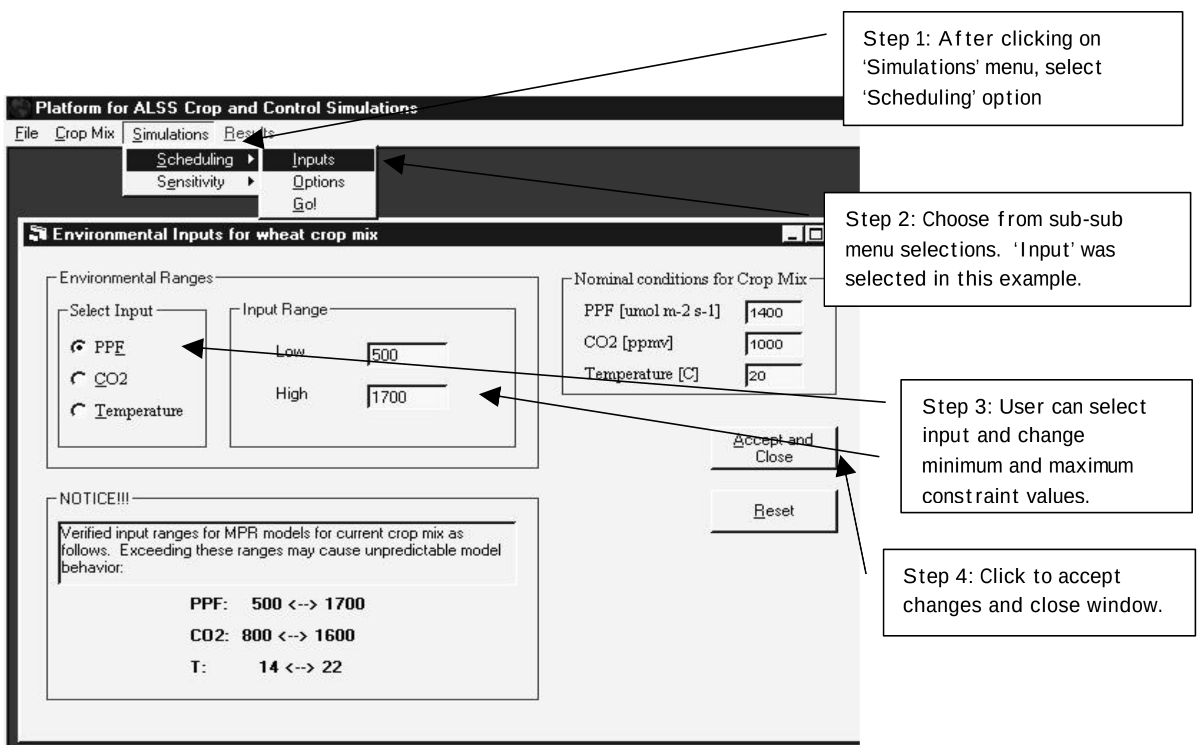

Figure 2: The 'Environmental Constraints' interface for PACCS' yield optimization routine.

For individual crops, the optimization routine searches for the set of environmental inputs that, within the given environmental constraints, will maximize either the crop yield at maturity [g m^{-2}] or the averaged yield growth rate [g m^{-2} d^{-1}]. Averaged yield growth rate is the ratio of the crop yield at maturity over the number of days in the production cycle (from transplanting to harvesting).

For multiple crop simulations, the optimization routine maximizes an objective function based on the summed yield potential for each crop in the crop mix as shown in equation 1:

$$OF = \sum_{i=1}^{n} \frac{V_i(MI)}{Max_i(MI)} \tag{1}$$

where:

OF - objective function used by PACCS optimization routine

n - number of crops in crop mix

$V_i(MI)$ - current yield mass or averaged yield growth rate at maturity date, MI, for crop i

$Max_i(MI)$ - maximum (highest observed) yield mass or average yield growth rate at maturity date, MI, for crop i

The second sub-menu, 'Options', lets the user select whether to optimize averaged yield growth rate [g m^{-2} d^{-1}] or the total yield at maturity date [g m^{-2}] (not shown). The 'Go!' sub-menu launches the optimization routine.

Selecting the 'Sensitivity' menu will allow the user to study the sensitivity of the selected crop mix production schedule to nominal and off-nominal environmental conditions. Production under constant environmental inputs with or without daily environmental disturbances can be simulated. If disturbances are included, PACCS will predict the effect of the disturbance on the production schedule, and will apply the model-based control algorithm to compensate for it. The user must first select the 'Inputs' sub-menu to open the 'Environmental Inputs' interface (Figure 3).

Within the 'Environmental Inputs' interface, users can select nominal inputs for the given crop mix, or use default values. Environmental disturbances can also be input. These are described with a starting date, a duration, and a percent magnitude off of the nominal value. The interface only allows input of a single disturbance for each environmental input. However, PACCS does allow for environmental disturbances in each of the three inputs to overlap along the course of the production schedule.

Selecting the 'Control' submenu opens an interface for changing the control weights used by the model-based predictive controller algorithm. There are three weights, one for each environmental input. In general, increasing the weight will result in a decrease in the control use of that input. However, this response also depends on the weights used on the other inputs.

Following the simulation of either the scheduling or sensitivity routines, the 'Results' menu (Figure 4) is enabled, and the user may select different methods for displaying simulated results. The first option is to select the 'Summary' submenu. This brings up a window which summarizes relevant production information such as maturity date, total biomass, yield, harvest index, and averaged growth rates over the production cycle. When a disturbance is simulated, three columns of data appear. Column 1 shows simulated results under constant environmental conditions, where no environmental disturbances are simulated. Column 2 displays simulated results with the environmental disturbances but without the control action. Column 3 includes the control action. For multiple crop mixes, columns 2 and 3 will display the disturbance results without control action.

A similar window is opened up if the Scheduling simulation routine is used (Figure 5). The following gives yield optimization growth rate results with a wheat and soybean crop mix.

The second method to display results is termed 'Specifics' and allows for time-history plots or spreadsheets of growth and environmental inputs to be displayed on the monitor. The user can select any variable for plotting by selecting desired variables (interface not shown). PACCS constructs graphs or spreadsheets based on these selections. For example, in Figure 6, time history graphs from a white potato simulation are shown. The plot on the left shows the yield dry mass [g m^{-2}] per day for three different scenarios, nominal simulation with no disturbances, disturbances, and disturbances with the control action. The plot on the right shows the daily values for light intensity used in each of the three scenarios. Similar curves can be obtained for temperature and CO_2 concentration.

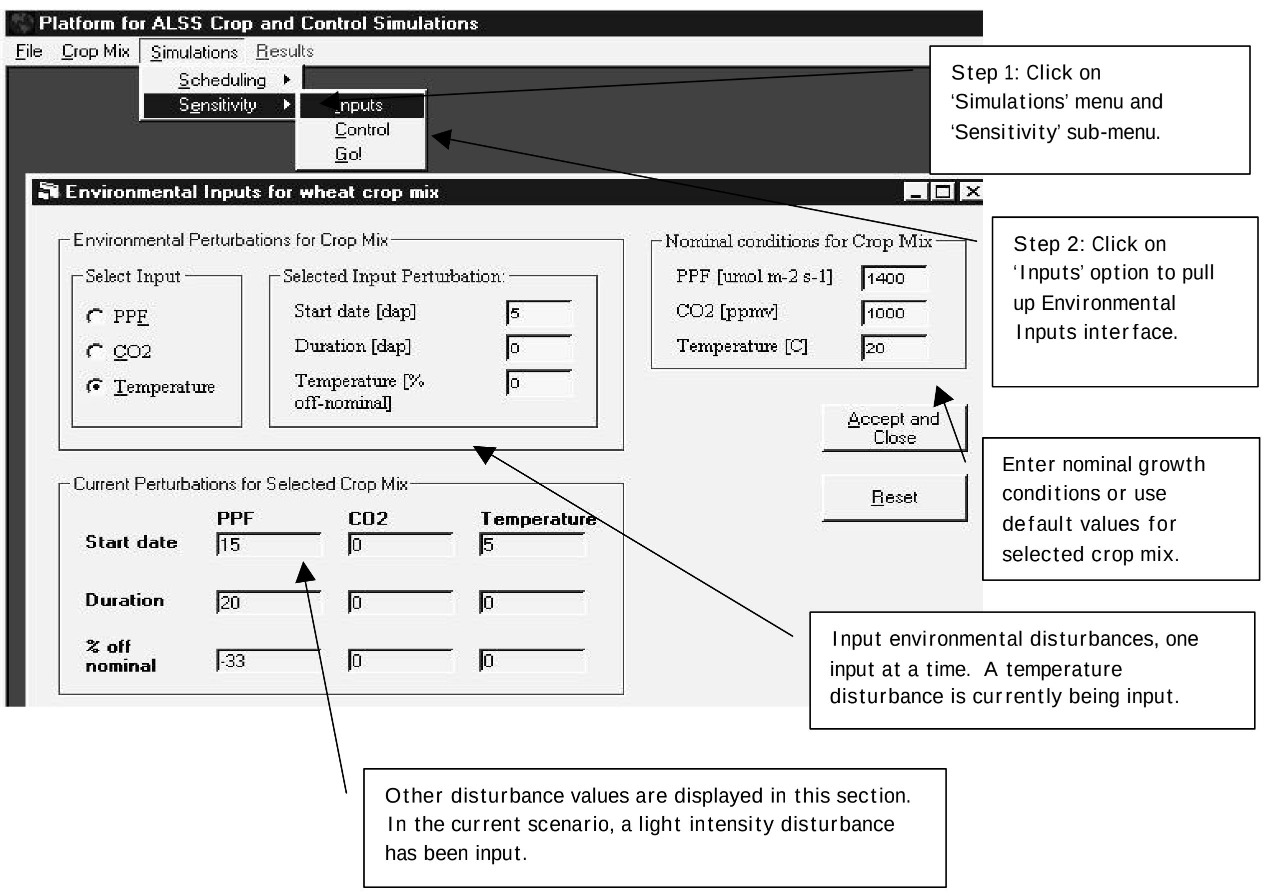

Figure 3: Environmental Input interface for the 'Sensitivity' simulation.

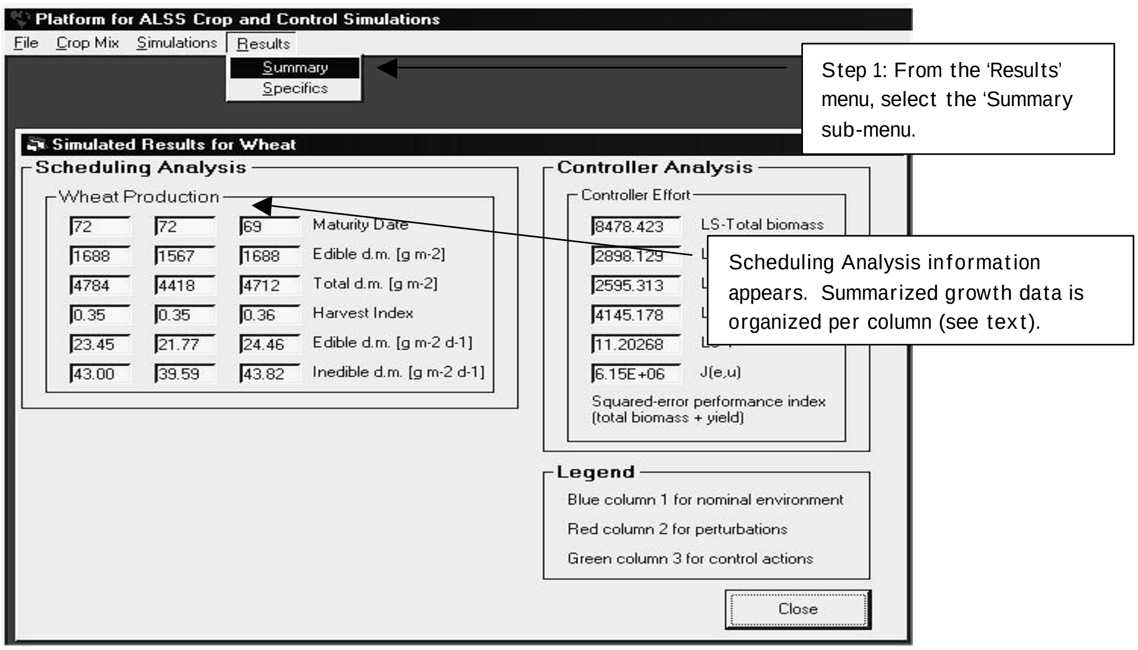

Figure 4: 'Summary' results screen with scheduling analysis information.

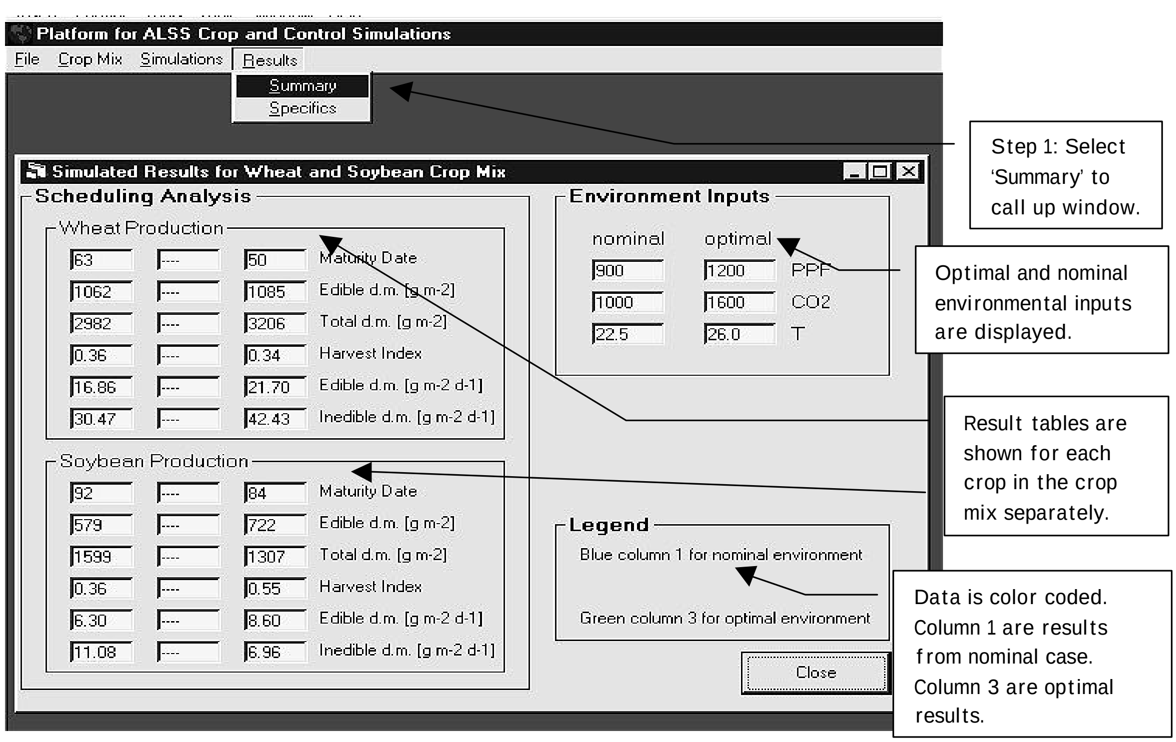

Figure 5: 'Summary' results window for a multiple crop simulation with wheat and soybean.

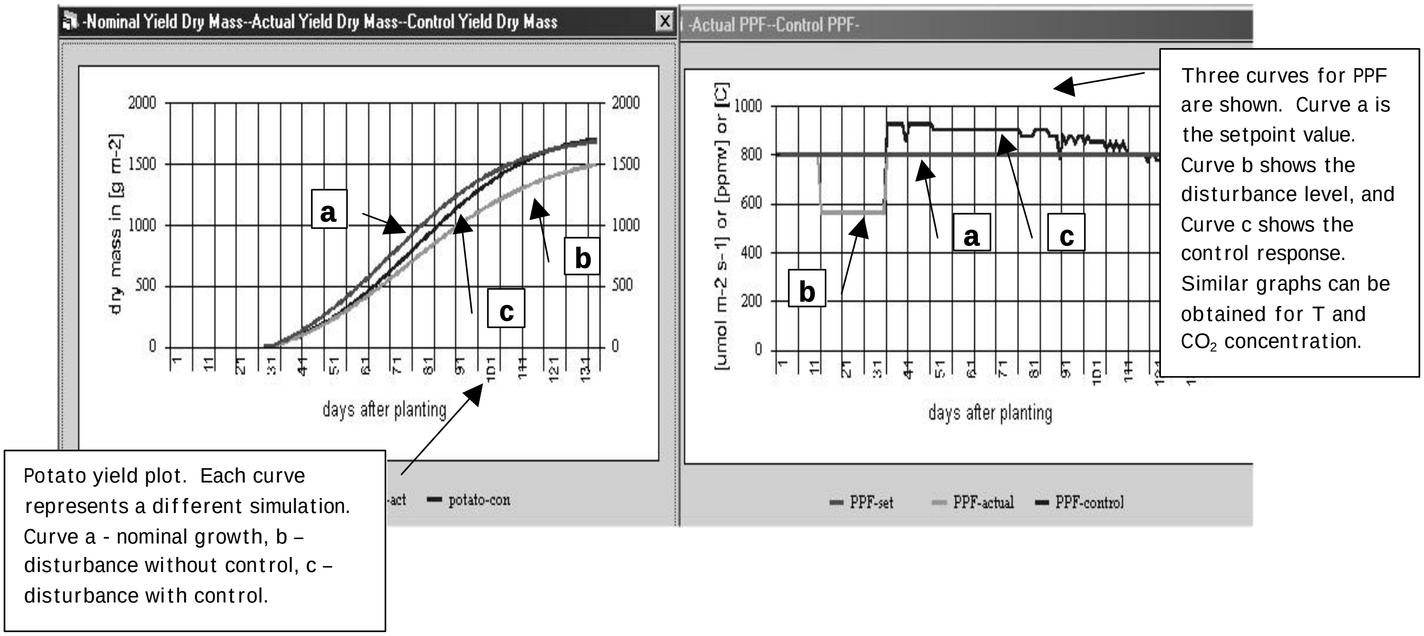

Figure 6: Time-history plots for a simulation with white potato. A disturbance scenario was simulated with baseline values of 800 µmol m^{-2} s^{-1} PPF, 20 ºC, 1000 ppmv CO_2 for a 20 day, -30% disturbance in PPF starting at day 15.

Discussion

PACCS simulations are proof-of-concept results and will require validation. However, the MPR and DSSAT crop models were developed based on existing knowledge (i.e., information from experiments carried out for model development, as well as literature or personal communication with other researchers). As such, there are many applied uses of the software even at the current stage of development. The manner in which PACCS was programmed allows the ALSS researcher to explore different options in crop production scheduling. The yield optimization tool in the 'Scheduling' routine automatically searches for environmental conditions to maximize yield for the selected crop mix. This routine also applies for multiple crop mixes as shown in Figure 5. Because the results indicate that it is feasible to grow crops under shared zones, the routine is useful for NASA engineers and scientists to design production schedules for possible biomass production component configurations.

The 'Sensitivity' routine allows study of sensitivity analysis of crop production to different levels of the environmental inputs (Figures 3, 4, 6). Again, these results can aid design and planning of ALSS crop production schedules because they estimate the maturity date and biomass production of crops under different combinations of environmental inputs. Such information can be used to define required production areas and make recommendations for sizing and selecting cultural facility equipment (e.g. desired level of light intensity can be used to determine type and number of lamps in the system).

PACCS also includes provisions for researchers to study effects of disturbances in the environment on production scheduling. The results can be used to determine if desired production can be met, if the current crop production scheme should be abandoned, and if it is possible to compensate for the disturbance. Simulations with the model-based predictive control algorithm (Figure 6) show that this is a viable method to aid the operation of a biomass production component.

Conclusions

A software program, PACCS, was developed to provide NASA engineers and scientists with decision support for designing, planning, and operating a biomass production component in an advanced life support system. Simulations can be performed to study single and multiple crop production scenarios, sensitivity analysis, and control actions to compensate for environmental disturbances on plant growth and development. Predicted time-series and growth analysis data can be obtained from the software.

A methodology to integrate expertise in plant biology, systems engineering, mathematical modeling, and control systems theory served as the conceptual foundation for PACCS. Although the number of available crops and environmental inputs limits the software, this approach can be implemented by NASA researchers to further the scope and validity of the tool. Thus, PACCS is also useful in identifying holes in the ALSS crop knowledge base and methods for performing future research.

PACCS was implemented as an open-loop decision support tool. Crew members must input measurements of the environment into its interface to obtain results. A future improvement to the software is to directly feed measurements from growth chamber sensors into the program. To close the control loop, automatic sensing methods for non-destructive measurements of crop growth could be input to the model-based predictive control algorithm. Such a step would serve to validate the control and realign the MPR model predictions at each time-step.

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