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Welcome to Virtual Grower 2.5

Thank you for your interest in Virtual Grower. Since we released Virtual Grower 1.0 in early 2006, we have attempted to work with representatives from the greenhouse industry to improve the software's capabilities. In this latest release, you will still find the ease-of-use and simplicity of the original software, but with many added features such as predicting plant growth and development for select species, improved descriptions of air infiltration into your simulated greenhouse, and additional energy curtain options. We have added supplemental lighting features and improved the calculations for energy curtains. If you have a connection to the internet while you are running the software, you can take obtain two-day forecasts of weather and simulate the short-term heating and lighting needs during these times.

Many features have been added over the years, and the vast majority of those have been added based on suggestions from users. As always, we want to hear from you. If you have a problem, complaint, or suggestion, please send us an email at USDA-ARS@utoledo.edu and we will respond to you inquiry as soon as possible.

Setup Requirements

Virtual Grower 2.5 is only compatible with computers running Microsoft Windows 98, ME, 2000, XP, Vista or later. It does not operate on 64-bit processors. Additionally, the computers must have the Microsoft .NET Framework version 2.0 in order to run the program.

Installation

If you already have a copy of Virtual Grower

Virtual Grower 2.5 will not install on your computer if you already have version 2.0 or later installed. Please follow the uninstall directions below before continuing with the installation of the new version.

Virtual Grower 2.5 is, however, a separate program from version 1.1 or earlier, and will install without altering the previous version. Since Virtual Grower 2.5 retains all the functionality of the previous versions, we recommend removing older versions of Virtual Grower. To install Virtual Grower 2.5 just follow the normal installation instructions below. All of your pre-existing greenhouse-saved files will remain intact and will still be available in the new version. However, saving any greenhouses with the new version makes them un-readable in an older version since many new features have been added. This should only be a problem if you revert to using an older version of Virtual Grower after you had installed and used this version (2.5) of the software.

If you have Virtual Grower 2.0 beta or 2.5 beta installed, you will need to uninstall it first following the instructions below. After uninstalling the beta version, proceed with the new installation following the normal instructions below. Please note that when loading files that were saved in the beta version, you will have to remove and reselect plant species.

Installing Virtual Grower 2.5 from a downloaded file:

First, create a temporary directory on your hard drive (e. g. C:\VGInstall) to store the downloaded and extracted installation files. Open your browser and enter the following URL in the address bar: www.virtualgrower.net and go to the "download now" link.

Enter the required information in the download form at the bottom of the page and click the "Take me to the download" button. Click on the Virtual Grower install file and select 'Save'. Within the 'Save As" dialog box, browse to the folder you have just created and click save. Open the newly created folder and double click on the "VG2_5Install.exe" file you have just downloaded to extract the installation files. Choose to "Run" the software, if asked. In the extractor dialog box, click on the "…" button and browse to the folder you created and click "OK". Click "Extract" to extract the install files; the window will automatically close when it is finished extracting. Finally click on the "setup.exe" file in the created folder to launch the installer and follow the onscreen directions. Please note that Virtual Grower 2.0 requires the Microsoft .Net Framework 2.0. If prompted to connect to the internet and download the framework, please choose to do so. The file is large and might take more than 20 minutes to download if your internet connection is a dial-up type. If you are unsure of your computer's framework status, run "Window's Update" and the appropriate files will be installed.

Installing Virtual Grower 2.5 from a CD:

Insert the Virtual Grower 2.5 CD into your CD-ROM drive. On most computers, the installation program will run automatically. If it does not, navigate to 'My Computer,' open the CD-ROM and run the program called 'Setup.exe'.

The setup program first checks to see if your computer has the Microsoft .NET framework version 2.0. If it does not, you will be asked if you would like to download the framework from Microsoft. If you have an Internet connection, choose to do so and allow the framework to be installed. Depending on your Internet connection, this could take anywhere from five to twenty minutes. Once the framework is installed (or if it was already installed), the setup program will guide you through the installation of Virtual Grower 2.0. Usually, the default options will work fine and you will only have to click 'Next' a few times.

If you do not have an Internet connection available and still need the Microsoft .NET Framework, navigate to 'My Computer,' right-click the CD-ROM drive, and run the program called 'dotnetfx.exe.' Follow the instructions to install the framework from the CD and then repeat the Virtual Grower installation steps above.

After the installation has completed, an icon will be added to your desktop and to your start menu labeled 'Virtual Grower.' Open either of these to run the program.

Uninstalling Virtual Grower 2.5

If you would like to uninstall Virtual Grower 2.5 or any earlier versions of the software, go to your start menu and open the Control Panel. When the panel opens, find and open the icon named, 'Add and Remove Programs'. Toward the

bottom of the list will be an entry for Virtual Grower 2.5 (or other version's number). Highlight it and click the 'Remove' button on the right. This will completely remove the program from your computer but will not delete your saved greenhouses. Also, uninstalling Virtual Grower will not remove the Microsoft .NET Framework. It is advisable to leave the framework on your computer since many programs are starting to require it. However, if you would like to remove it, follow the same instructions as above but look for an entry called "Microsoft .NET Framework version 2.0" instead. You may have to close programs that are currently running and/or restart your computer after removing the framework.

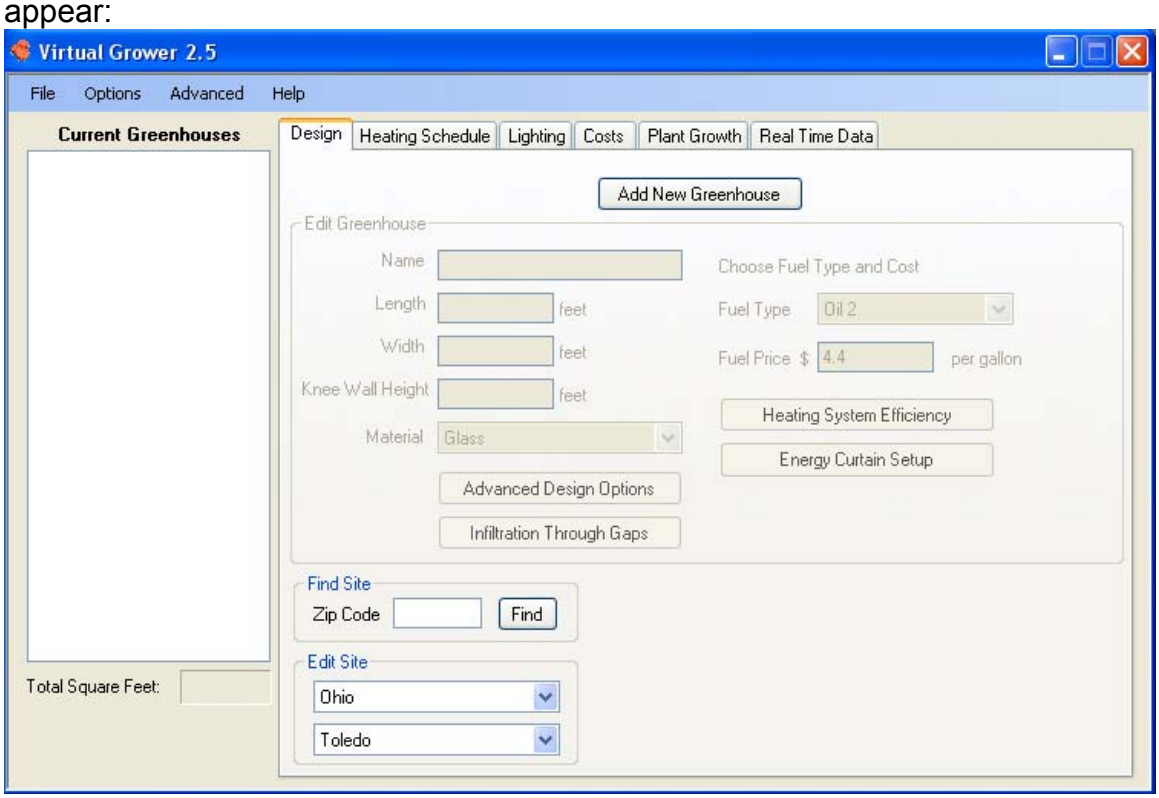
Repairing a Virtual Grower 2.5 Installation

If your installation of Virtual Grower 2.5 becomes damaged or will no longer run properly, insert the Virtual Grower 2.5 CD and run the Setup program (or just run the setup.exe program if you downloaded it). When the installer asks if you'd like to repair or remove Virtual Grower 2.5, choose 'Repair,' click 'Continue', and follow the remaining instructions. This will reverse problems associated with installing older versions of Virtual Grower on a computer that already has Virtual Grower 2.5 installed.

If you have downloaded the software and have difficulty installing it, please contact USDA-ARS@utoledo.edu and we will gladly mail you a CD with the software and necessary framework at no cost.

Getting Started

Once installed, double click on the Virtual Grower icon (the one with the picture of flowers) on your desktop or in the start menu. The Main Page should appear:



At the top of the page, there are tabs labeled “Design,” “Heating Schedule,” “Lighting,” “Costs,” “Plant Growth,” and “Real Time Data.” By clicking on the tabs, those sections will appear.

Design

Four boxes are outlined on this page: Current Greenhouses, Edit Greenhouse, Find Site, and Edit Site.

Current Greenhouses

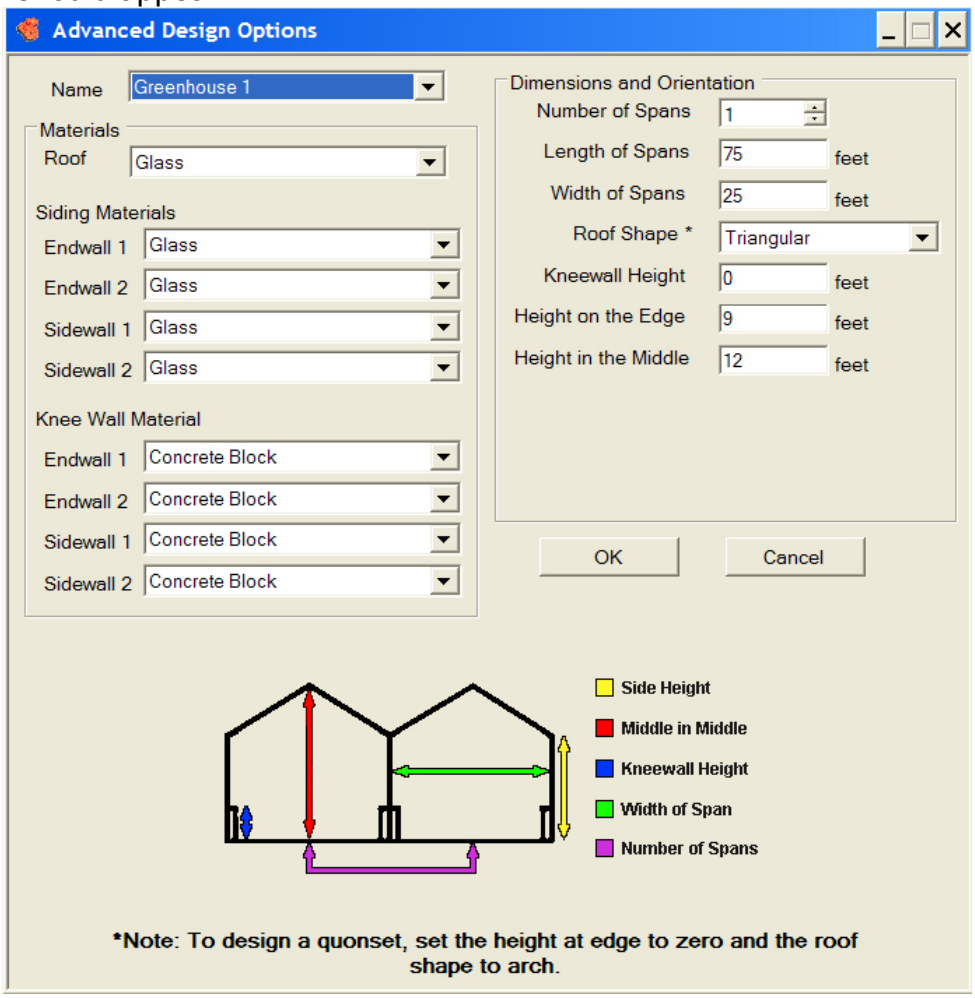
This displays a list of greenhouses that have been created within Virtual Grower. Upon opening the program, there are no greenhouses in the list. When the button “Add New Greenhouse” is clicked once, a greenhouse name appears in this list next to a box that can be checked or unchecked by clicking on the greenhouse name in the Current Greenhouses list. You can also load previously developed greenhouses from other Virtual Grower sessions by clicking File<Load Settings, and selecting from a list of saved greenhouses. When a greenhouse is added to this list, the Total Square Feet of all greenhouses (checked and not checked) is shown at the bottom, left corner.

Edit Greenhouse

After a greenhouse has been added (by clicking “Add New Greenhouse” or loading a previous greenhouse), the Edit Greenhouse section allows you to name the greenhouse and define the size and shape of that house. By clicking in each section (Name, Length, Width, Kneewall Height, Material, Fuel Type, and Fuel Price), you can type in the information specific for that greenhouse. For example, if you have several greenhouse zones and some are gutter connected poly houses, you may name the initial greenhouse Zone 1, and define the dimensions (in feet) of your greenhouse and the height (also in feet) of your kneewall. If you do not have a kneewall, enter 0. You can choose the material of your greenhouse from the drop-down list next to the Material section. This assumes that the *entire greenhouse*, other than the kneewall, is made of that material. When a greenhouse is constructed of different materials, it is necessary to further refine the design of your greenhouse. To do this, click on the Advanced Design Options button.

Advanced Design Options

After clicking on the “Advanced Design Options” button, the following screen should appear:

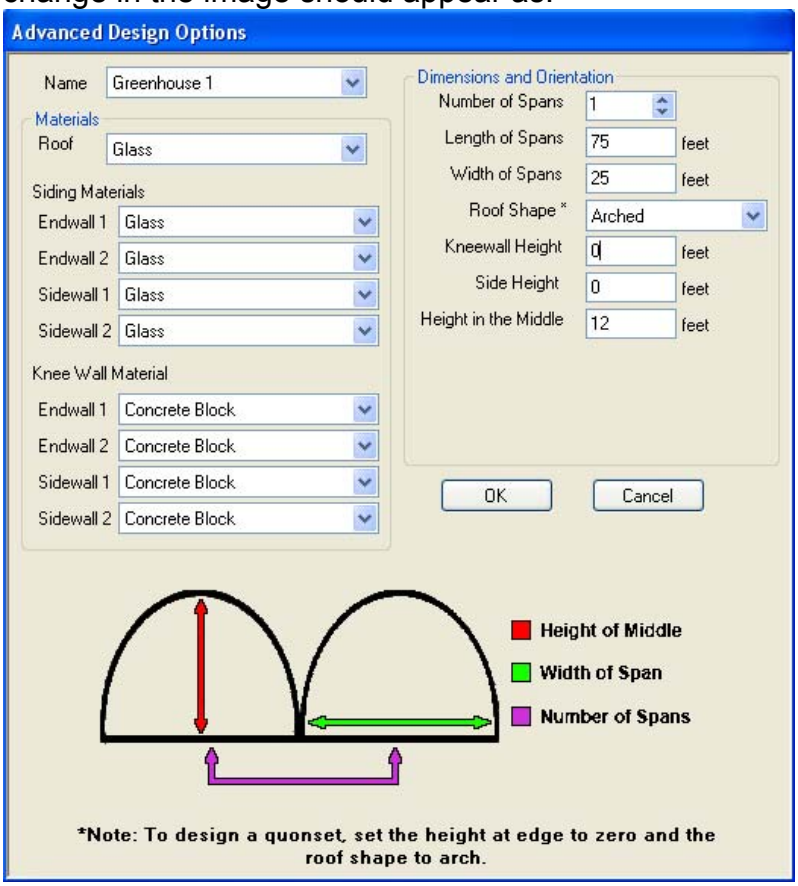


This page allows you to change roofing, endwall, sidewall, and kneewall materials from a pre-determined material list as a whole and for each side,

independently. Additionally, you can change the sidewall and center heights, greenhouse style, and if a gutter-connected greenhouse is being constructed, choose the number of spans within the structure. Note that if you are designing a gutter-connected house, the width to be entered is for each span, post to post, not the width of the entire house.

At the bottom of this screen is a picture of the greenhouse type you are constructing. Even though the picture shows a two-bay gutter connected house, it does not mean all greenhouses are gutter connected. The greenhouse will be gutter connected only if the number of spans (top box in the right corner of the Dimensions section) is greater than one.

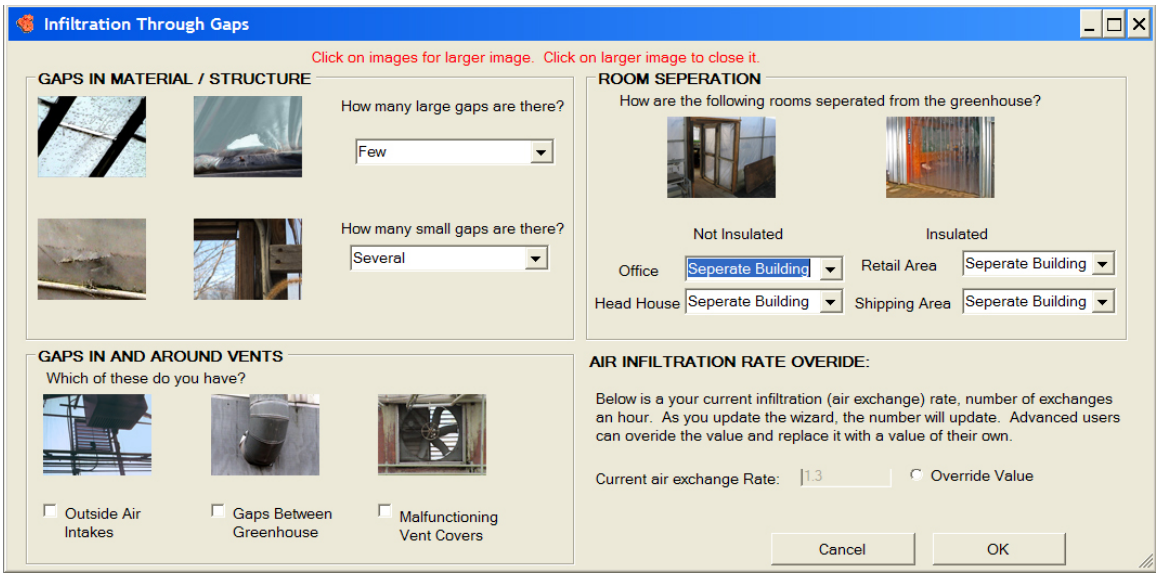
Quonset-style greenhouses can be built in this section. To build a Quonset house, set the height at the edge to zero and select the roof shape as "Arched." A change in the image should appear as:



Once the settings are completed to your satisfaction for this greenhouse section, you can either click "OK" at the bottom of the screen or choose a different greenhouse section or zone to modify from the drop-down panel next to "Name". When "OK" is clicked, you should return to the main page.

Infiltration Through Gaps

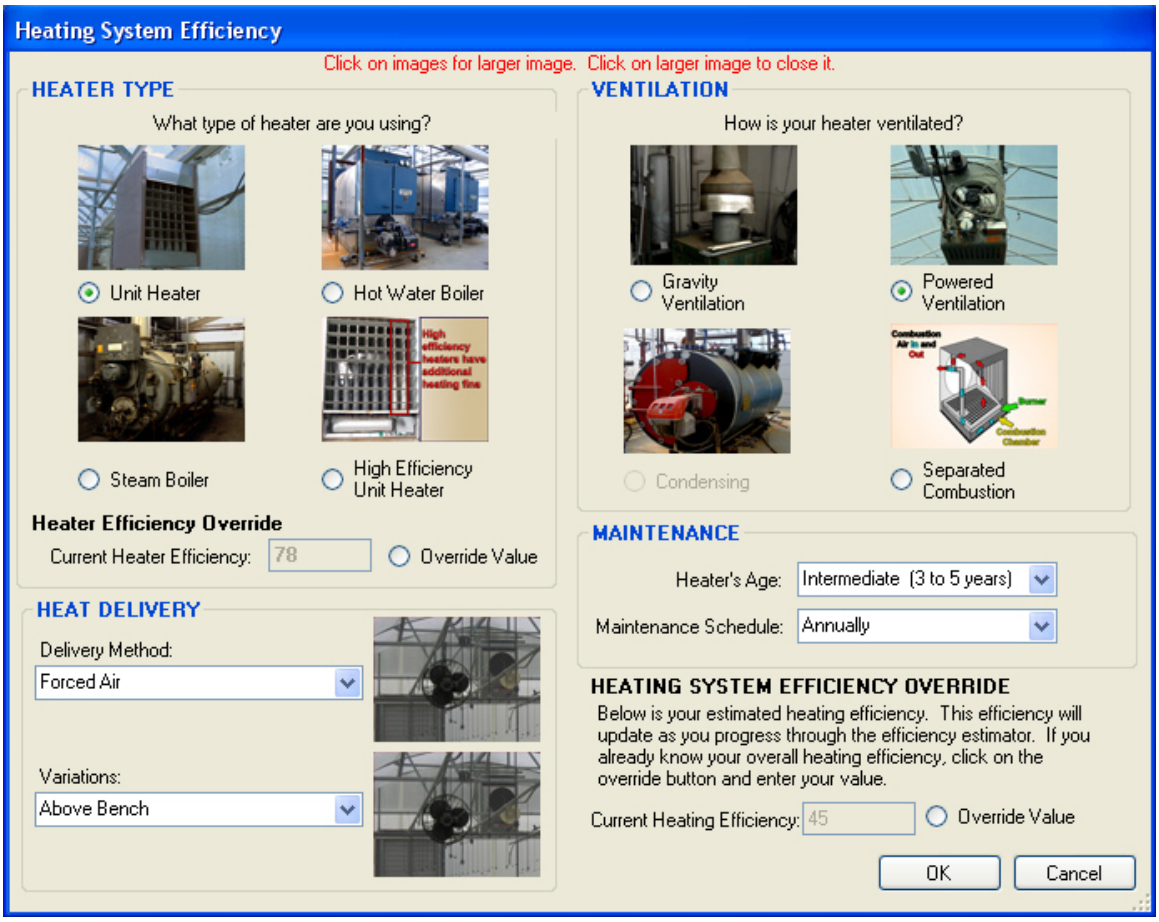
Infiltration Through Gaps refers to the tightness of your greenhouse construction and helps describe leaks throughout a greenhouse or greenhouse section. Clicking on this should show the following page:



There are four sections to this page. GAPS IN MATERIAL / STRUCTURE allows you to define the number of large and small gaps you may have in that particular greenhouse. If you are unsure of what a gap of this type looks like, view the picture or click one to enlarge it. Clicking on an image again will close the enlarged picture and return you to the Infiltration Through Gaps page. GAPS IN AND AROUND VENTS allows you to state if you have one or more of the gap types often found in operating greenhouses. ROOM SEPARATION addresses heat losses commonly experienced, though often ignored, in head house, office, or shipping areas. Each time a description is entered, the air exchange rate is changed, which can be seen in the section AIR INFILTRATION RATE OVERRIDE section. If you want to see the impact that different air exchange rates may have on your greenhouse or if you know your air exchange rate, click the override button and enter a value (air exchanges of your greenhouses per hour) here. Once you have completed the Infiltration Through Gaps Section, click the OK button. You will then return to the Main Page. **Note** that the air exchange rate estimated in the Infiltration Through Gaps section will be applied only to the house that is highlighted (selected) on the main page in the "Current Greenhouse" window, regardless of the checked or unchecked box status. The Infiltration Through Gaps section should be treated as a tool only – it is not a substitute for a thorough analysis by licensed engineers.

Heating System Efficiency

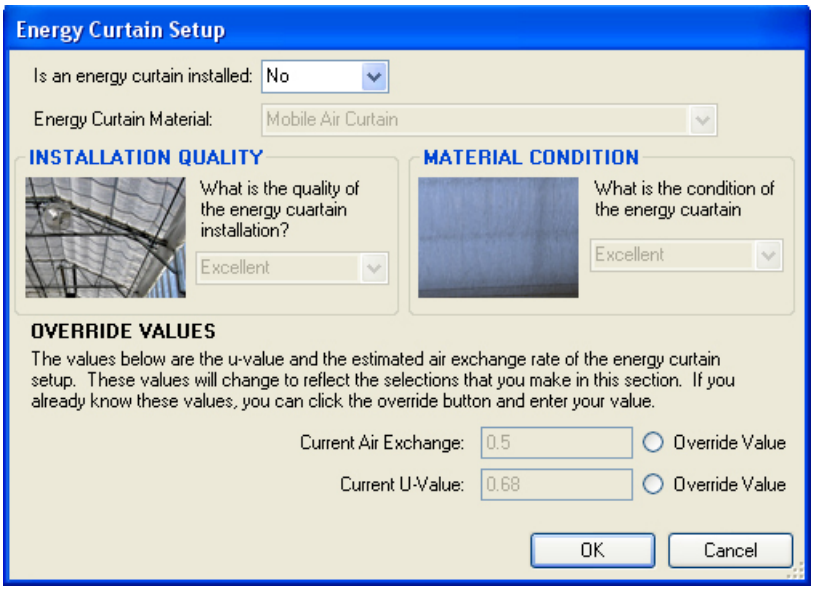
Heating System Efficiency describes the overall heat system efficiency from heater or combustion efficiency through delivery of that heat to the growing area. Clicking on the Heating System Efficiency button will show the following screen:



There are five sections to this page. As you click through each section to describe your heating system, an estimate of overall heating efficiency is estimated. HEATER TYPE allows you to select one of four types of heaters that are commonly used in greenhouse production. If you do not see your heater type or if you already know your heater's efficiency, you can click on the "Override Value" button and enter your current heater's efficiency. VENTILATION describes how your heater is ventilated. HEAT DELIVERY describes heat exchangers and delivery method of the heat to your growing areas. The drop down menus and photographs will change depending on the heater type and ventilation selected in those sections. In the MAINTENANCE section, select the heater's age and maintenance schedule that best describes your system. Finally, the HEATING EFFICIENCY OVERRIDE provides the estimate of the heating efficiency of your system based on the heater type, ventilation, delivery, and maintenance selections. Alternatively, if you know your overall efficiency, you may click on the "override value" button and enter an efficiency value, from 0 to 100. Once you have completed the Heating System Efficiency section, click the OK button. **Note** that the heating system efficiency that is estimated in this section will be applied only to the house that is highlighted (selected) on the main page in the "Current Greenhouse" window, regardless of the checked or unchecked box status. The Heating System Efficiency section should be treated as a tool only – it is not a substitute for a thorough analysis by licensed engineers. Clicking on the OK or Cancel buttons will return you to the Main Page.

Energy Curtain Setup

The Energy Curtain Setup section allows you to describe an energy curtain system for the selected (highlighted) greenhouse being simulated. Clicking on this button should show the following page:



At the top of this page, you can select “yes” or “no” to indicate having an energy curtain system installed in the selected greenhouse. The default setting is no energy curtain. If “yes” is selected, you can select the curtain material from the drop down menu, describe the Installation Quality, and Material Condition. Together, these selections define the air exchange rate between the section of greenhouse above and below the energy curtain, and the U-value of the curtain system. These are used in the calculations to determine the potential savings of your described system. [see Appendix 2 for more information on how energy curtain calculations are made]. The pictures will not change based on curtain material. If you are unsure of the curtain material but know air exchange and/or the U-value of the material, you can select the Override Value button and enter these values manually. Once you have completed the Energy Curtain Setup section, click the OK button. **Note** that the Energy Curtain Setup values that are estimated in this section will be applied only to the house that is highlighted (selected) on the main page in the “Current Greenhouse” window, regardless of the checked or unchecked box status. The Energy Curtain Setup section should be treated as a tool only – it is not a substitute for a thorough analysis by licensed engineers.

Fuel Type

Fuel Type allows you to select the type of fuel used to heat that greenhouse while Fuel Cost allows you to input the cost of that fuel.

Find Site

In this box, you can enter your zip code (US only) to find the nearest weather database site.

Edit Site

In this box, you can select a state and city at which you can construct your greenhouses. The default settings are Toledo, Ohio. Selecting a state will load cities corresponding to that state. Not all cities within a state are represented, so choose one that is closest to you if your city is not represented. [if you are unsure of the closest location, enter your zip code in the Find Site box.] For example, in the state of Ohio, a user in Bowling Green would choose the city of Toledo since Bowling Green is not currently in our database. [Still can't find a city that's close to yours? Contact us at USDA-ARS@utoledo.edu and we will work with you to try and find one that best suits your needs.]

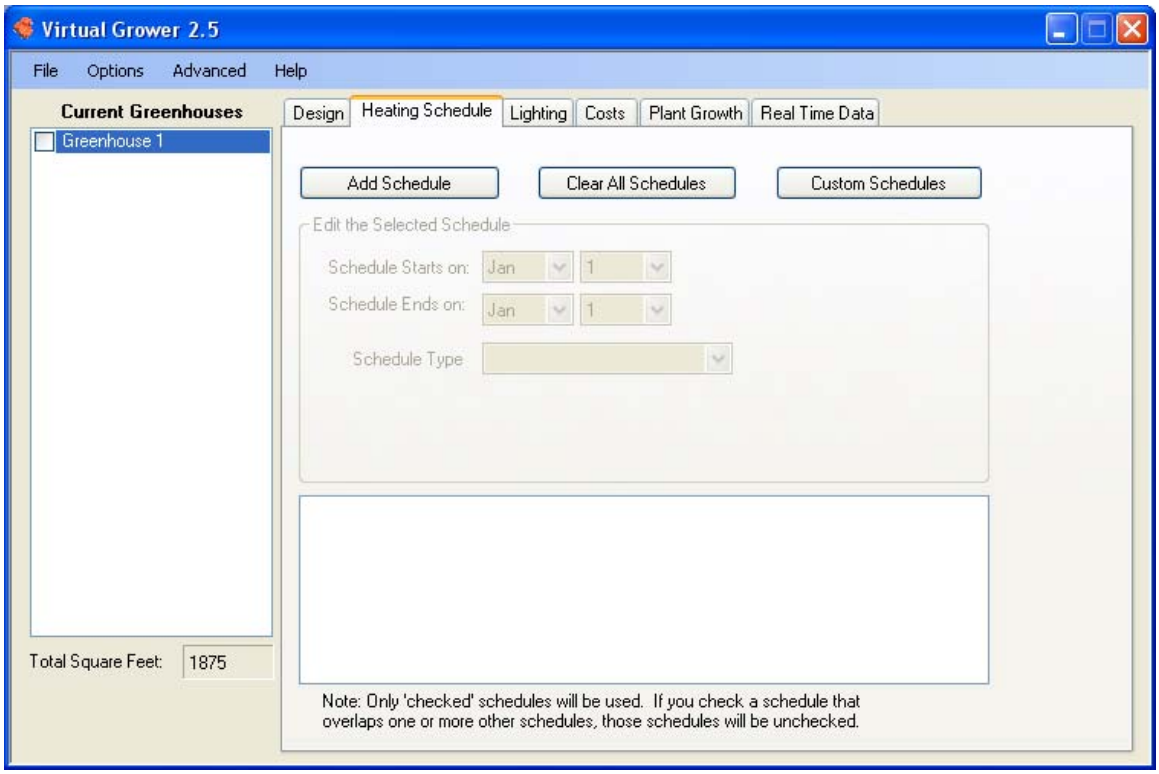
By selecting a city and state, a historical database for typical weather at that location is loaded, which gives typical values of temperature, light, and cloud cover, for example, for each hour over the course of 12 months. This weather information was obtained from the National Renewable Energy Laboratory website (http://rredc.nrel.gov/). It is important to note that the weather information is not average values for a period of time, but typical or representative values for that date and time.

Saving

At any time during simulation or "constructing" your greenhouse, you can save the greenhouse setting from the Main page by clicking File<Save Settings and naming your design file. This enables you to reload your greenhouse in other Virtual Grower sessions. Exiting out of the program at any point will also prompt you to save your settings.

Heating Schedule

After clicking on the Heating Schedule tab, the following screen should appear:



This section allows you to select a greenhouse, highlighted in blue on the left side of the screen that was constructed in the Design section, and program a heating schedule for up to an entire year for that section. By clicking on the Add Schedule button near the top, an initial, default setting appears with a constant, year round temperature of 65°F. To program your own schedule that will accurately reflect your particular growing schedule, highlight the schedule in the box at the bottom and then choose a starting and ending date from the drop down menus on which the heat will be activated for that greenhouse. In the "Schedule Type" drop down menu, a list of No Heating, Its Day When The Sun Is Up, Its Day When I Say It Is, and Constant Temperature allows for four pre-determined heating types. The function of each selection is:

No Heating

Greenhouse is not heated so no cost is calculated for that house.

Its Day When The Sun Is Up

The daytime temperature setpoint is activated when the sun comes up, based on your location in the country. When the sun is not up, the night temperature is maintained. In this selection, the thermoperiod matches the natural photoperiod or light period.

Its Day When I Say It Is

The daytime temperature is set to specific time period in the day. This time period does not change from one day to the next.

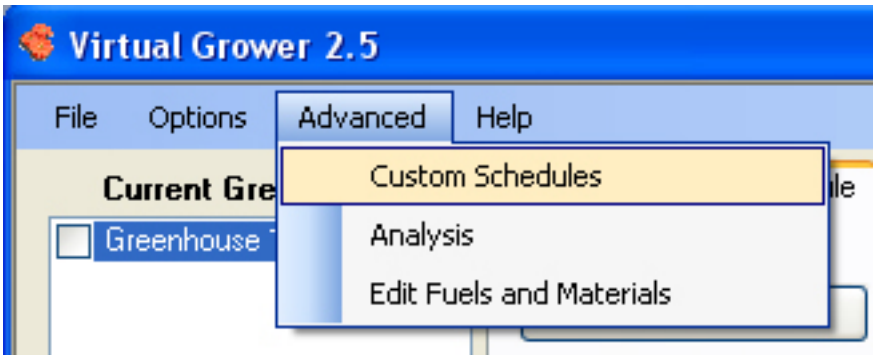
Constant Temperature

The temperature is the same, day and night, during the time period that is defined.

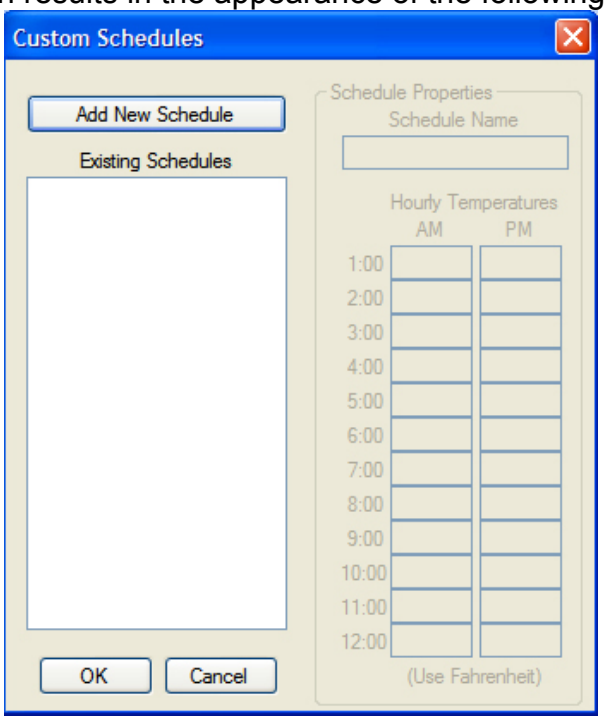
If you have a heating schedule that has more than two temperatures during a 24-h period, the Custom Schedules options allows you to set hour-by-hour temperatures.

Custom Schedules

To set hour-by-hour temperatures, either click on the Custom Schedules button or choose Custom Schedules in the Advanced drop down menu from the top of the window



Choosing this option results in the appearance of the following window:



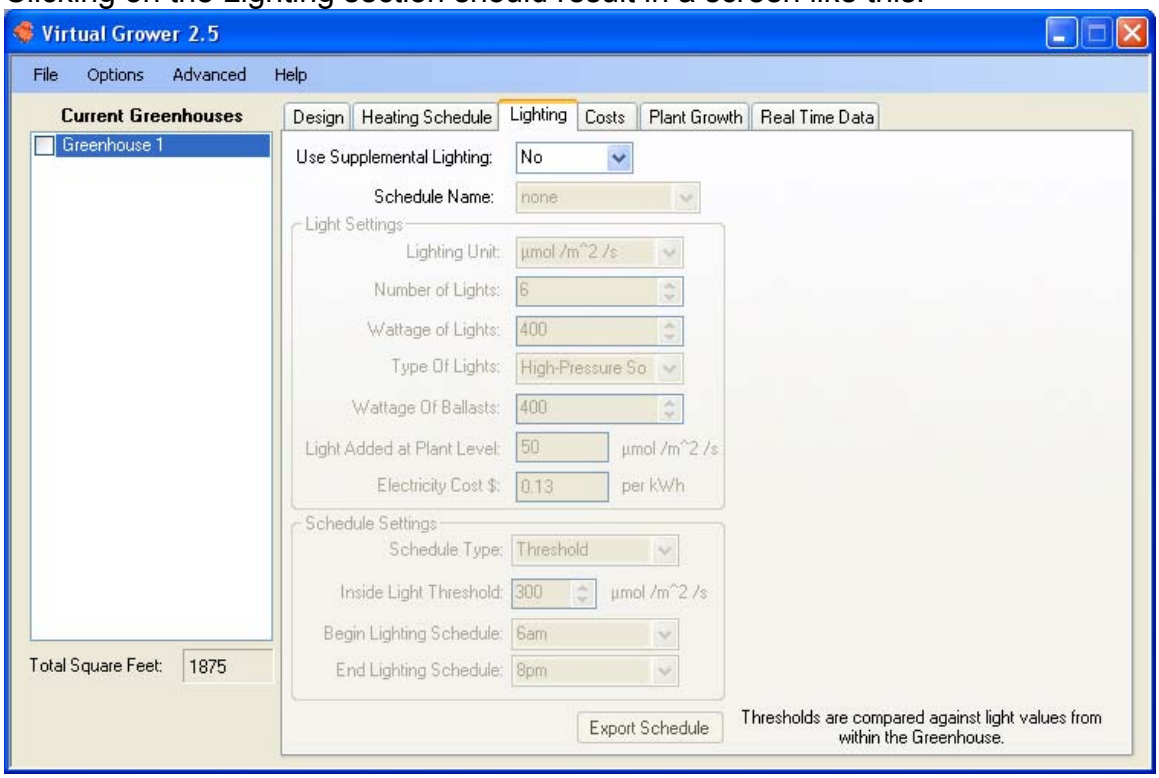
By clicking on the “Add New Schedule” button, hourly temperatures of 65°F are defaulted into the list of temperatures on the right of the window. Clicking in each window, you can change the specific temperature set point for each hour of each day. The value in this section is that you can program DIF or DIP treatments for certain crops or certain times of the year. Before clicking the OK button, name the schedule in the Schedule Name box (upper right). This will save that schedule and allow you to have that schedule for future greenhouse designs.

The program allows you to have complex, realistic scheduling for entire greenhouses, but currently, does not permit subdividing greenhouse sections with temporary partitions as is a common practice in greenhouse production.

To change greenhouses, click to highlight a different greenhouse from the Current Greenhouse list on the left. Once all greenhouses have been scheduled to your satisfaction, costs can be calculated for your greenhouses.

Lighting

Clicking on the Lighting section should result in a screen like this:



At the top of this page is a “yes” or “no” question asking if you have supplemental lighting in the greenhouse section selected (highlighted) on the left. The default value is “no,” which means that no supplemental (electric) lighting is used for this greenhouse section. If “yes” is selected, the settings are populated below, as indicated by black lettering (rather than light grey).

Just below the yes-no selection, you can name the lighting schedule. This is useful if you want to apply the same lighting schedule for different greenhouses. Below the schedule name are two boxes: Light Settings and Schedule Settings

Light Settings

This area allows a user to describe the light set up through entering the number of lights, wattage of bulbs and ballasts, lamp type, the amount of light the plants receive from the electric lamps, and your electricity costs. Make sure you select a lighting unit (µmol m^{-2} s^{-1}, footcandles, lux, and W m^{-2})!

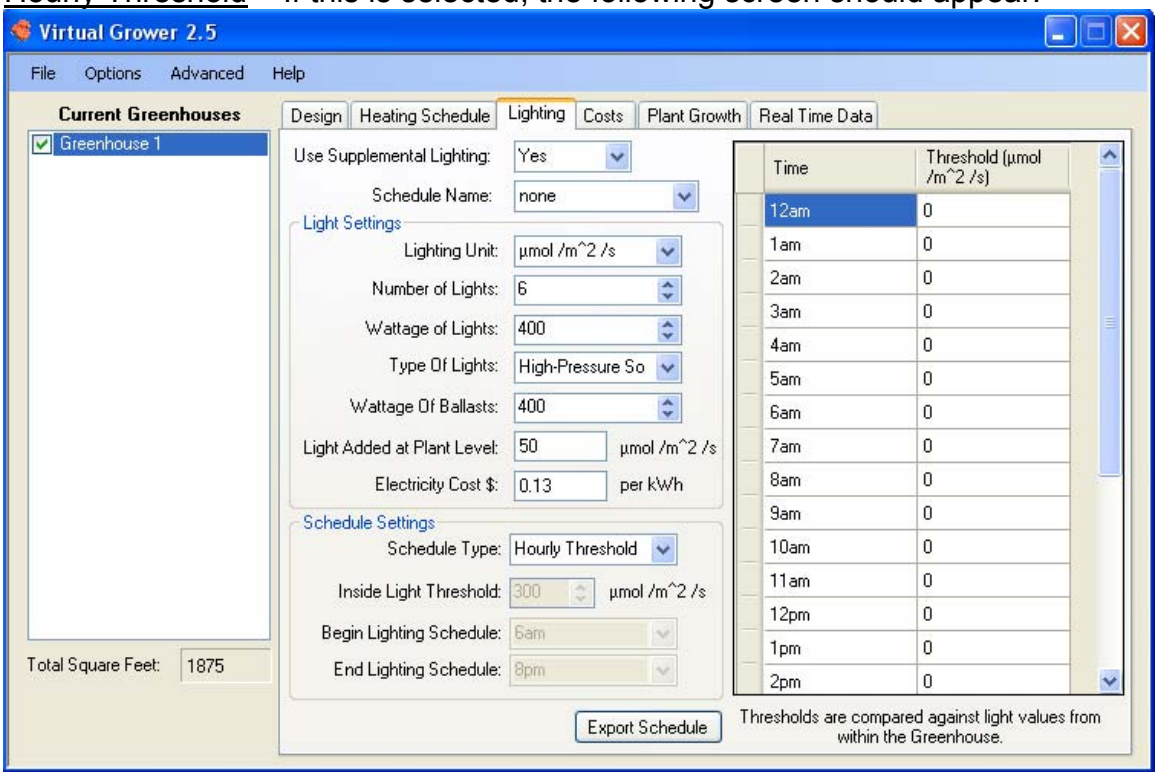
The selections made here will help determine the operating costs of supplemental lighting for a given greenhouse, as well as determine the potential

impacts that using supplemental lighting might have on plant growth and development (time to flower and size) in the Plant Growth section.

Schedule Settings

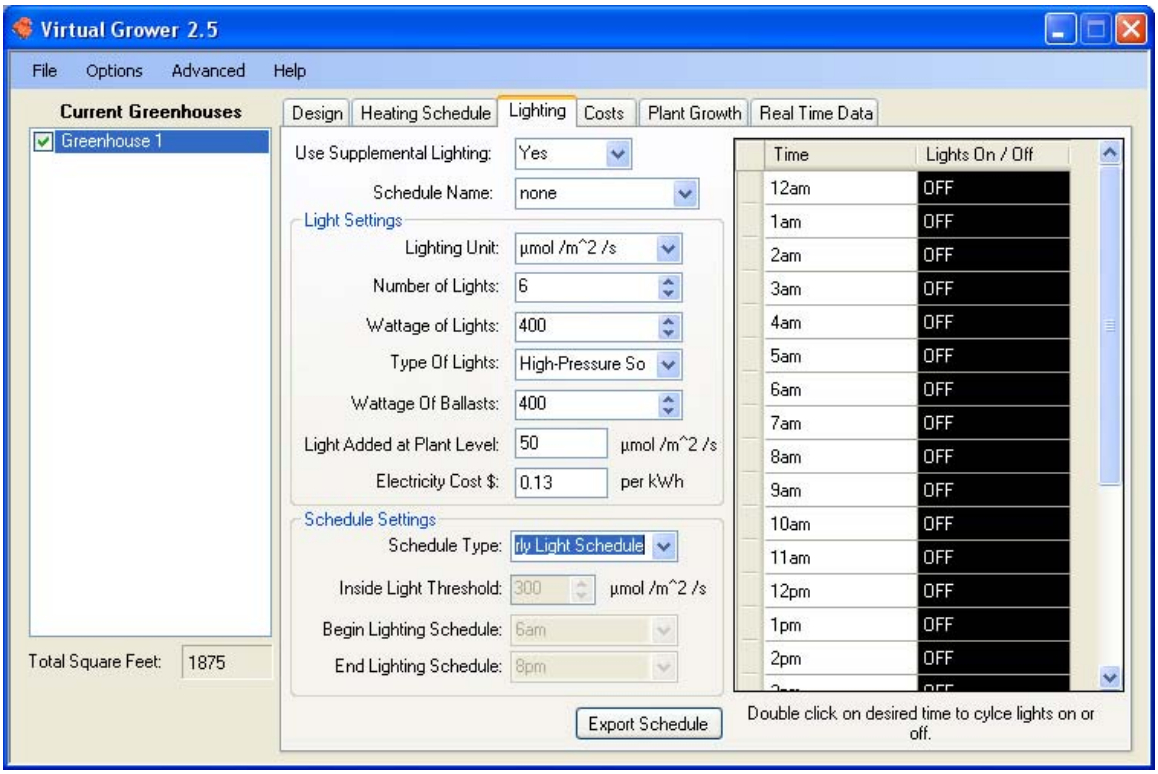
This area allows a user to describe how and when the supplemental light is utilized within a greenhouse. In the Schedule Type drop-down menu, there are four options from which to select: Hourly Threshold, Hourly Schedule, Threshold, and Light Schedule.

Hourly Threshold – If this is selected, the following screen should appear:



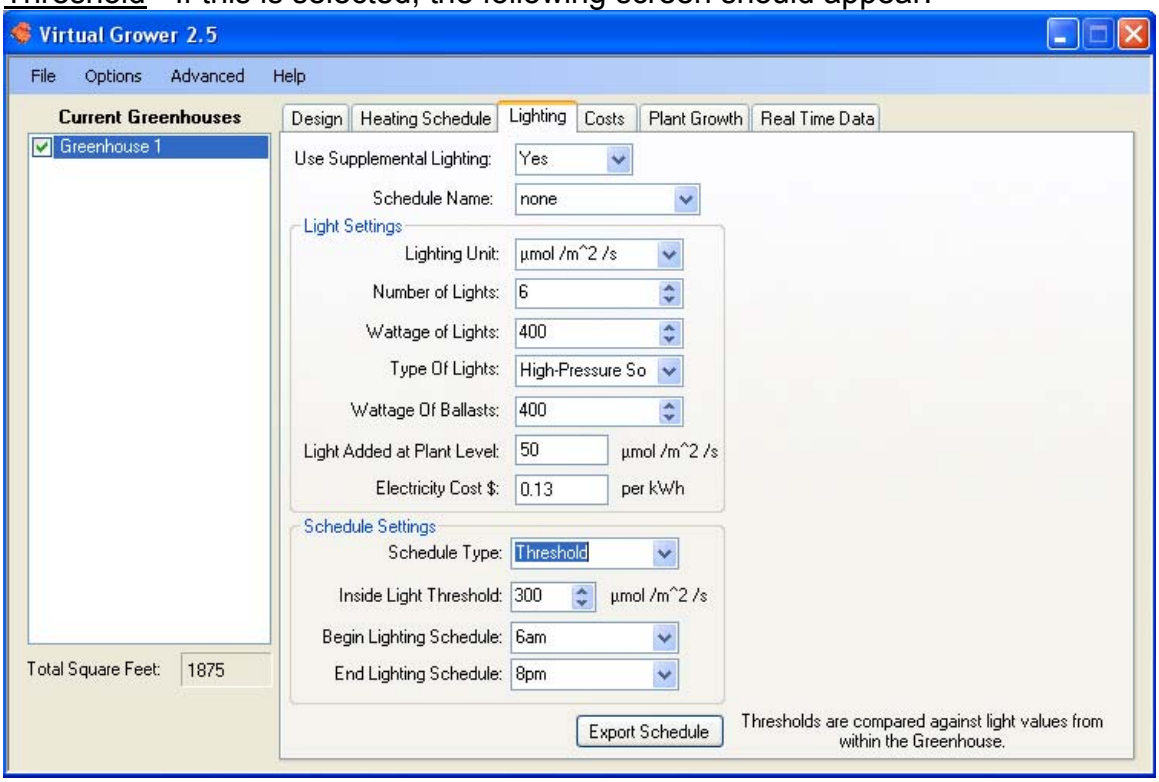
On the right side of this screen, you can enter, hour by hour, the lower light threshold (inside the greenhouse, based on greenhouse materials and historical or predicted weather information) below which your lighting system will activate. The user can enter different threshold values, below which your lighting system will activate. It is possible in this setting to have different thresholds for different times of the day. Note that when 0 is entered (default), the light will not activate at that hour.

Hourly Schedule – If this is selected, the following screen should appear:



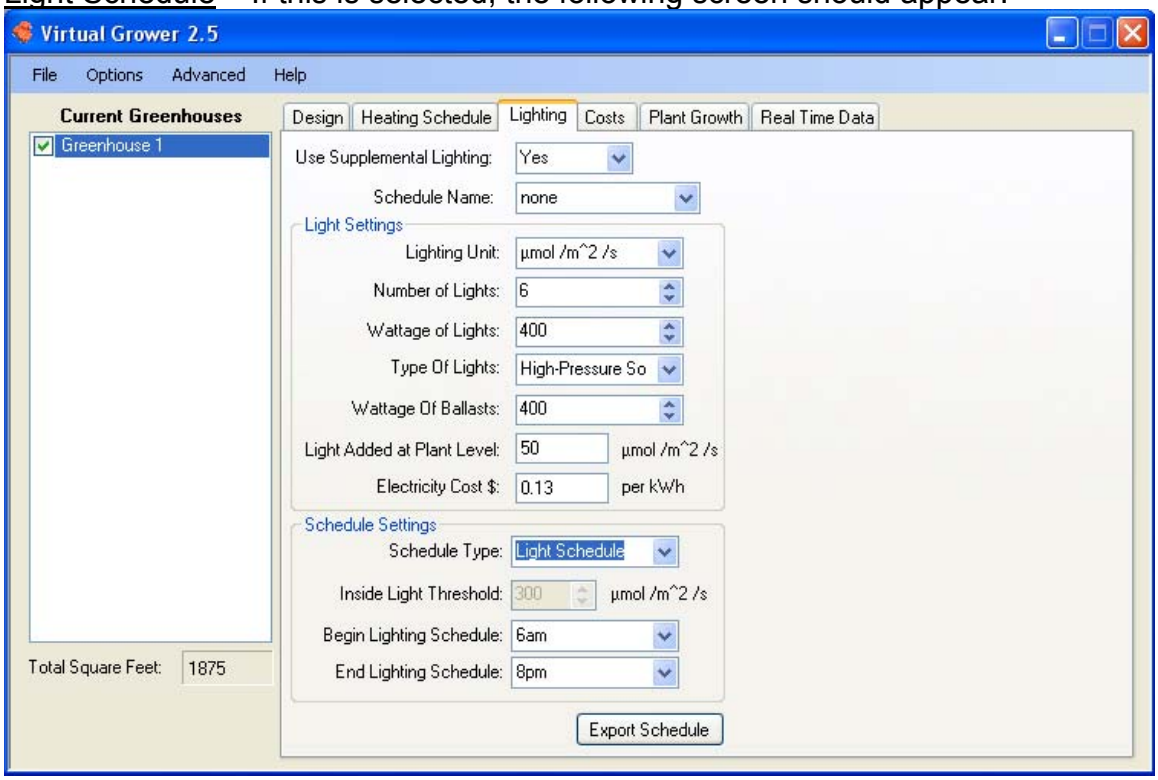
On the right side of this screen, you can activate, hour by hour, light system described in the Light Settings. This is useful for scheduled night interruption treatments or to take advantage of known low-electricity cost periods in your area.

Threshold - If this is selected, the following screen should appear:



This setting is useful to activate the lighting system when the light inside the greenhouse falls below a single threshold level between certain times. The threshold is entered (note the units are the same as the units selected in the Light Settings section) and the times during the day are selected during which the threshold will be utilized.

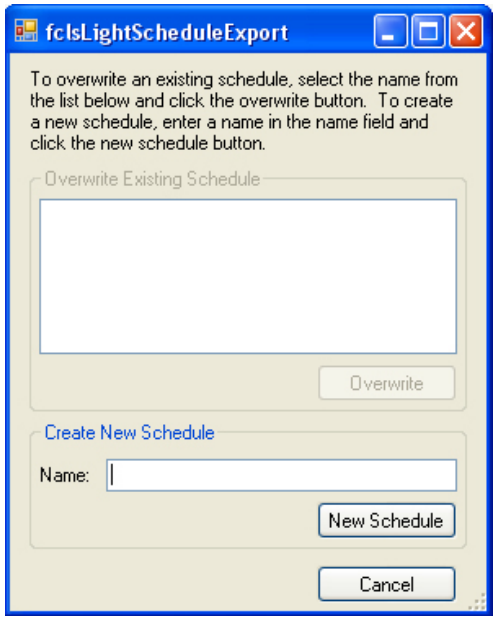
Light Schedule – If this is selected, the following screen should appear:



This setting is useful to activate the lighting system during a single, constant period of the day or night, regardless of other factors. The user chooses the start and finish times for when the lights are activated and turned off.

Export Schedule

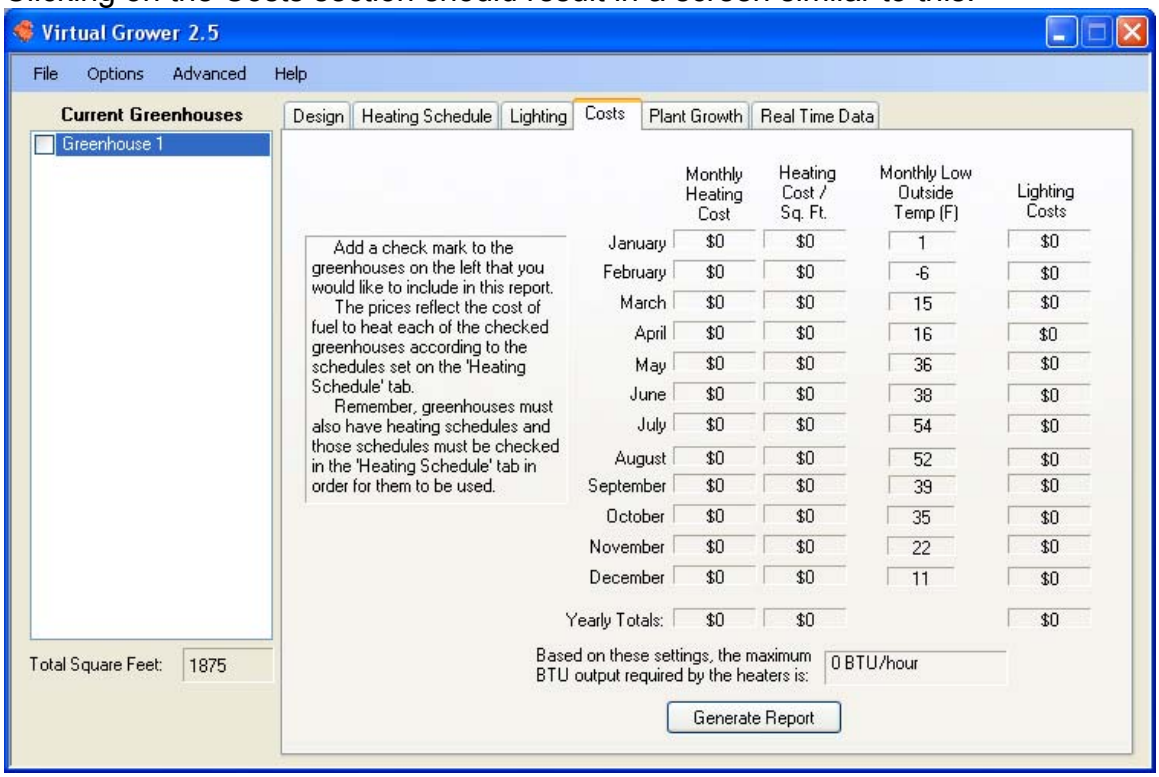
This buttons allows for a specific lighting setup to be applied to other greenhouses within the same simulation session or file. When this button is clicked, the following screen should appear:



Providing the name of the unique lighting schedule and clicking on "New Schedule" will save this lighting setup in the simulation file/greenhouse file, and will return you to the lighting page. This schedule can then be applied to more than one greenhouse by highlighting the greenhouse name on the left side of the screen, choosing "yes" to supplemental lighting, and selecting the new schedule name from the drop down list.

Costs

Clicking on the Costs section should result in a screen similar to this:



The actual screen you see will depend on your location (city and state chosen from the main page), lighting setup, and number and name of greenhouses in your modeling session.

On the right half of the screen, a list of the months, total monthly heating costs, costs per area, a list of the lowest temperature in that month, monthly lighting costs, yearly totals for heating costs and heating costs per area, and lighting costs. Also shown is a “maximum BTU output required” box that can be used to help predict the size of heaters needed to heat the greenhouse(s) selected for analysis. Note that if more than one greenhouse is selected (box checked) on the left of the window, this maximum BTU box will predict the maximum BTU output for the total of all selected greenhouses. See the Appendix 4 on how the maximum BTU output is calculated.

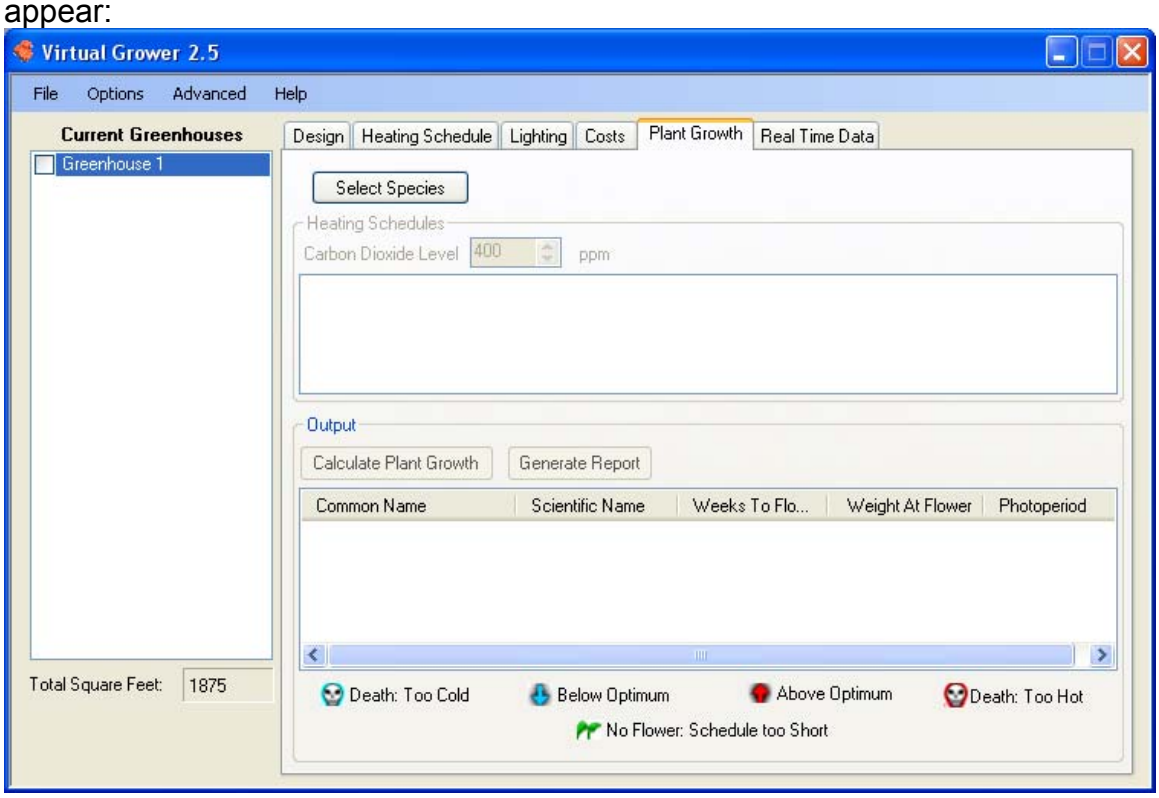
Note that the cost estimator will not calculate costs until one or more greenhouses are selected (with a check in the box next to the greenhouse name) and a heating schedule is assigned to the checked greenhouses. The costs displayed by month will then reflect the greenhouse structure, size, materials, and style as well as the heating schedules, fuel types for those greenhouses, energy curtains, and lighting schedules that were assigned to the different greenhouses.

Generating a Report

Clicking on this button brings up another window with text that describes the current settings (greenhouse design considerations, fuel types, etc.). You can select and copy this information to another word processing program to keep track of multiple scenarios easily or you can save this report by clicking on the save report button. The file saved is a .txt file that can be opened up in most word processing applications.

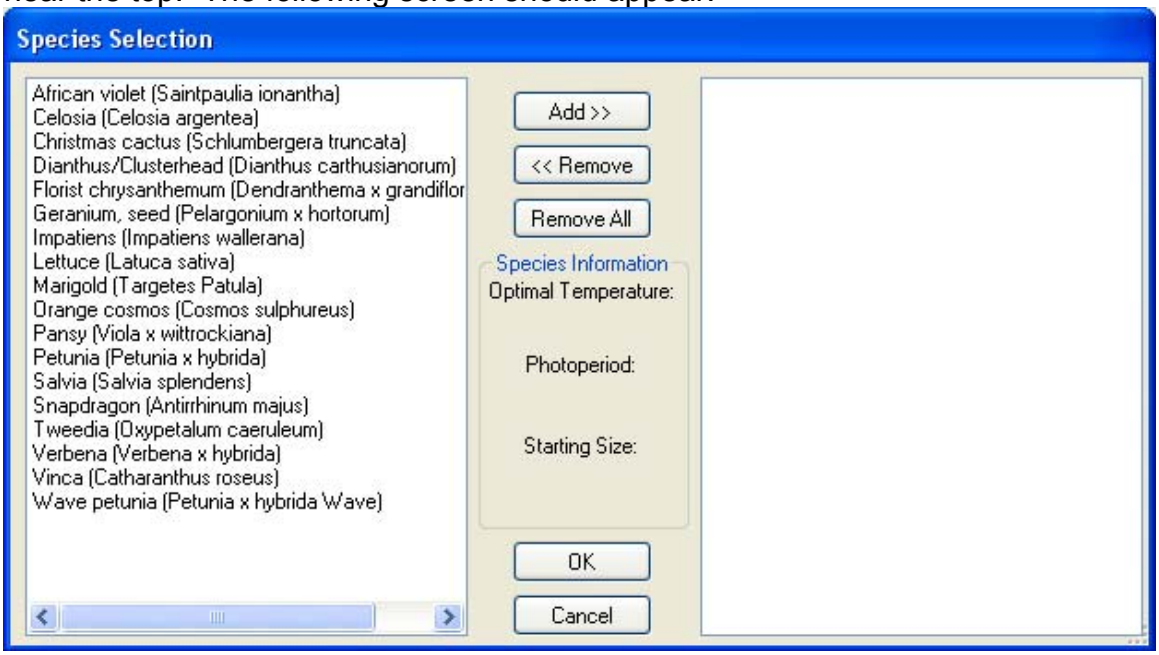
Plant Growth

By clicking on the “Plant Growth” tab, a screen similar to this should appear:

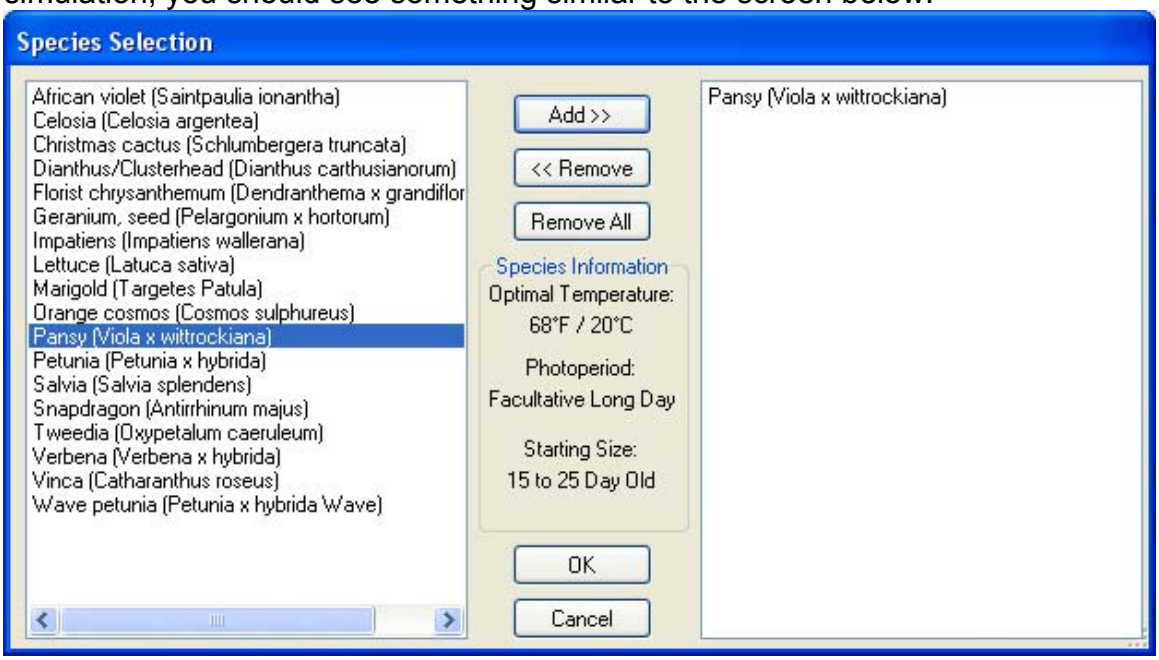


Selecting Species

Plant growth within Virtual Grower simulations is based on a database of 18 crops. To select your species of interest, click on the “Select Species” button near the top. The following screen should appear:



The crops are organized in alphabetical order by common name (most commonly used name based on a number of popular press, web page, and journal articles) and scientific/Latin name (Genus-species). Selecting a species is done by clicking on the plant on the left and the clicking on the Add button. After adding this plant, the plant should appear on the right side of this window. For example, if you select the popular bedding plant Pansy and add it to the simulation, you should see something similar to the screen below:



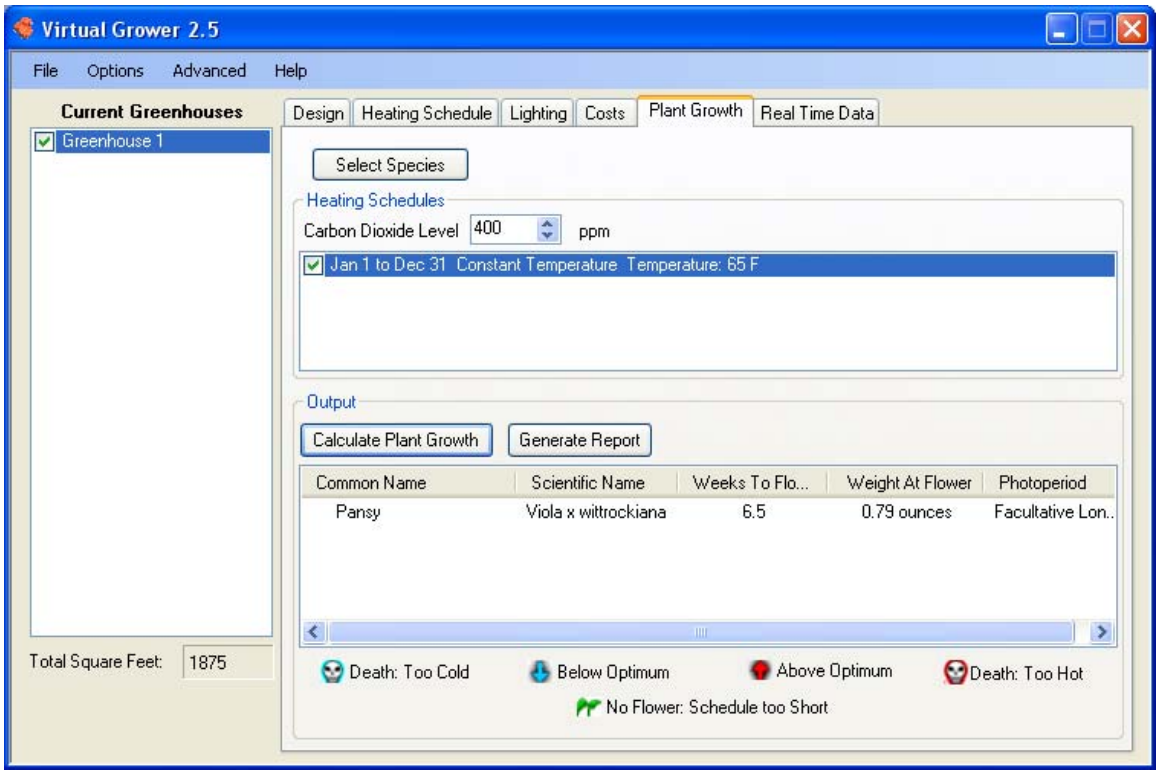
There is no limit to the number of plants that can be selected and simulated. In the middle of this screen, additional information about that species is provided including optimal temperature and photoperiod requirement. Also included is a reference starting plant size upon which the growth and development models are based. The optimal temperature shown on this screen is the center of a broad (~5-7 °F, 3°C) range of “optimum” development temperature.

If you select a species and no longer want to include it in the simulations, you may highlight it from the Selected Species box and click the Remove button once. Starting over can be accomplished by clicking the Remove All button once. After all your species are selected, click the OK button to return to the Plant Growth tab.

Calculating Plant Growth

To simulate plant growth, a heating schedule that was created in the earlier sections must be selected for that greenhouse. This action applies a specific environment to the species selected and enables predictions of plant growth (size, in fresh weight) and development (time to flower). Once a heating schedule is selected, two buttons in the Output section are activated. The Calculate Plant Growth button simulates plant growth and development for the species selected and puts values for time to flower (weeks to flower), plant size

at flowering (ounces or grams in fresh weight), and photoperiod requirement next to the crop names.



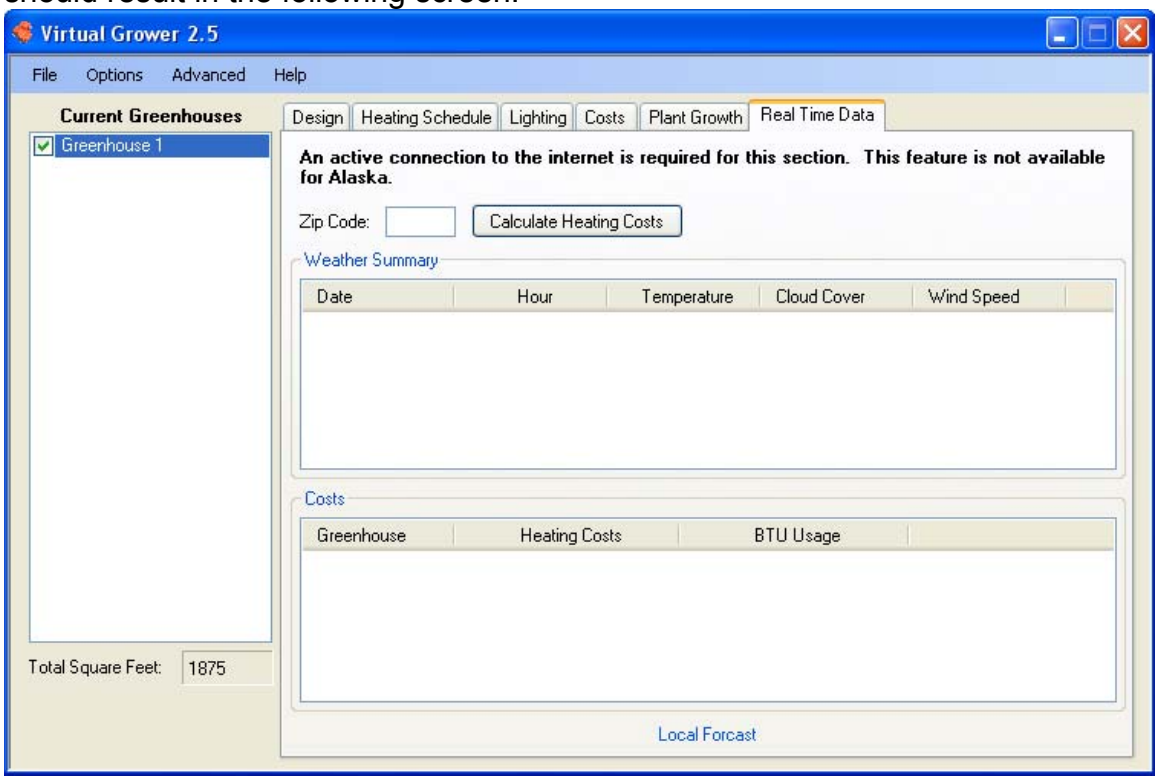
The simulations for predicting development assume that the inductive photoperiod is used for production, but for your convenience, the photoperiod required for proper development is reported. Lettuce, the only vegetable crop in Virtual Grower 2.5, is predicted only for growth (size). Instead of time to flower, two sizes are reported for two production lengths (4 and 6 weeks of growth). **Note that if supplemental lighting is utilized and the result of that schedule contradicts the inductive photoperiod for that species, no warning appears.**

Virtual Grower has developed a set of warning symbols for when plants are not experiencing their optimum environment. These symbols appear to the left of the plant name after growth is simulated. These symbols are meant to guide a user into either optimizing the environment for a given crop or warn a user of where plant performance may suffer if grown in the simulated environment. See Appendix 7 for symbol details. The symbols are based on temperature optima for development (floriculture crops) or vegetative growth (lettuce).

The CO_2 concentration can be changed for different simulations. The default setting is 400 parts per million (ppm; also $\mu mol\ mol^{-1}$) and can be increased or decreased in increments of 25 ppm. Currently, different CO_2 concentrations will only affect plant size at flowering (i.e. CO_2 will affect plant growth), not developmental rate.

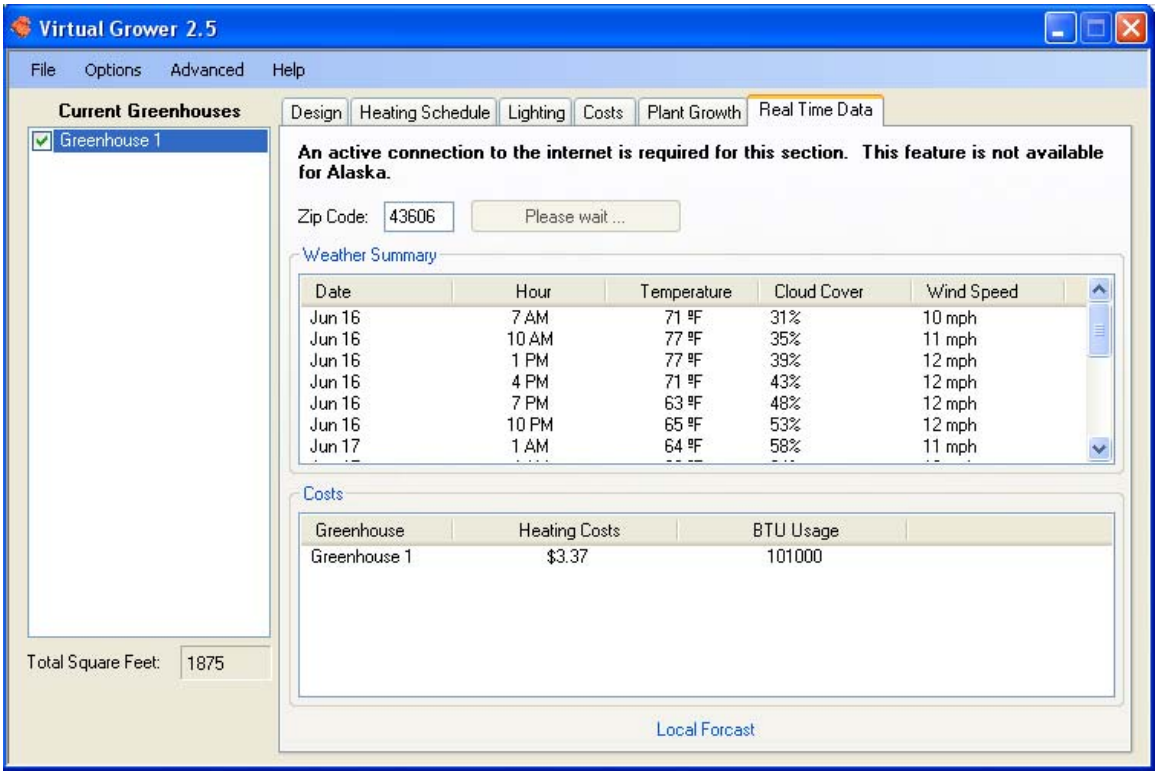
Real-Time Data

If you have an active internet connection, the Real Time Data section can allow you to check costs for heating over the next two days. Clicking on this section should result in the following screen:



Near the top of the screen, there is a box into which you can type your five-digit zip code. When the zip is entered, click once on the "Calculate Heating Costs" button. The button should appear as:

During this time, Virtual Grower is retrieving the two-day forecast from the website forecast.weather.gov that is specific to your zip code. In a few seconds, the forecast will appear in the top box, broken down in 3-h increments, and the costs for each selected greenhouse and its BTU usage will appear in the bottom box as appears below:



The heating costs prediction (and screen that you will see) depends on the greenhouses simulated and heating schedule. This feature is only functional for US sites, except Alaska.

The button next to the zip code box will remain in the “Please wait…” mode for a minute. This is to prevent too many data calls to this website, and lessens the risk of the website crashing.

At the bottom of the screen, you can click for the local forecast. Clicking here will take you to the website forecast.weather.gov, and if you have entered a zip code in the upper box, the forecast screen will display the radar at that location. This is useful to verify the zip code function is working properly.

Additional Options from the Drop-Down Menus

Import -> Greenhouses

This tool allows you to load previously saved greenhouses into Virtual Grower, just like the normal 'Load Settings' function. However, instead of replacing any greenhouses that you are currently working on, the import function will add them to the list. For example, if you had a saved greenhouse file with two greenhouses in it and were working on two others, importing the saved file would add two greenhouses to the list for a total of four. Saving your settings will save all the greenhouses to a new file, not to the ones you have imported from. Also note that any custom schedules associated with the greenhouses in the import file will also be added to Virtual Grower's custom schedule list.

To use it, on the main menu, click 'File,' then 'Import,' and finally 'Greenhouses.' A window will pop up asking you which file you would like to

import greenhouses from. You can choose from any saved greenhouse files you've made from Virtual Grower. Find the file you would like, select it, and click 'Load.' The greenhouses from that file will then be added to the list.

Import --> Custom Schedules

This tool allows you to use custom schedules you or someone else has made previously in Virtual Grower. By importing a 'Custom Schedules' file, all of its saved schedules will be added to Virtual Grower's list of custom schedules and will be immediately available for use in any of your greenhouses. Note that once custom schedules have been imported, they will be on Virtual Grower's list until you delete them, even if you restart the program. This means that you only need to import any given set of schedules once, so long as you don't delete them.

To use it, on the main menu, click 'File,' then 'Import', and finally 'Custom Schedules.' A window will pop up asking you the name of the file you would like to import schedules from. You can choose from any exported custom schedules files made by Virtual Grower. Find the file you would like, select it, and click 'Load.' The schedules saved in that file will then be added to the list.

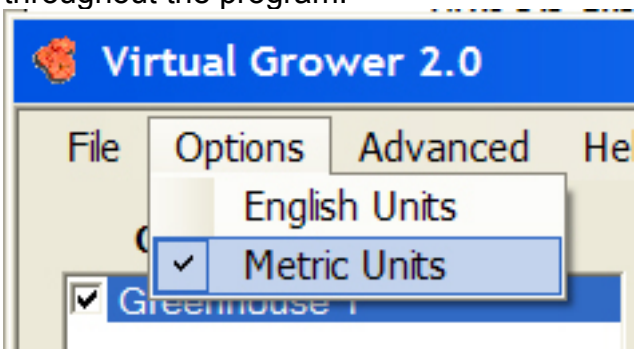
Export --> Custom Schedules

This tool allows you save any custom schedules that Virtual Grower is using to a separate file. This can then be used to retrieve those schedules if they ever get deleted or changed and also allow you to share custom schedules with other Virtual Grower users.

To use it, on the main menu, click 'File,' then 'Export,' and finally 'Custom Schedules.' A window will pop up asking you to choose a file name and location for your custom schedules file. Type a name in the box and choose an appropriate folder and then click 'Save.' All of your custom schedules will now be coped to the new file.

Units

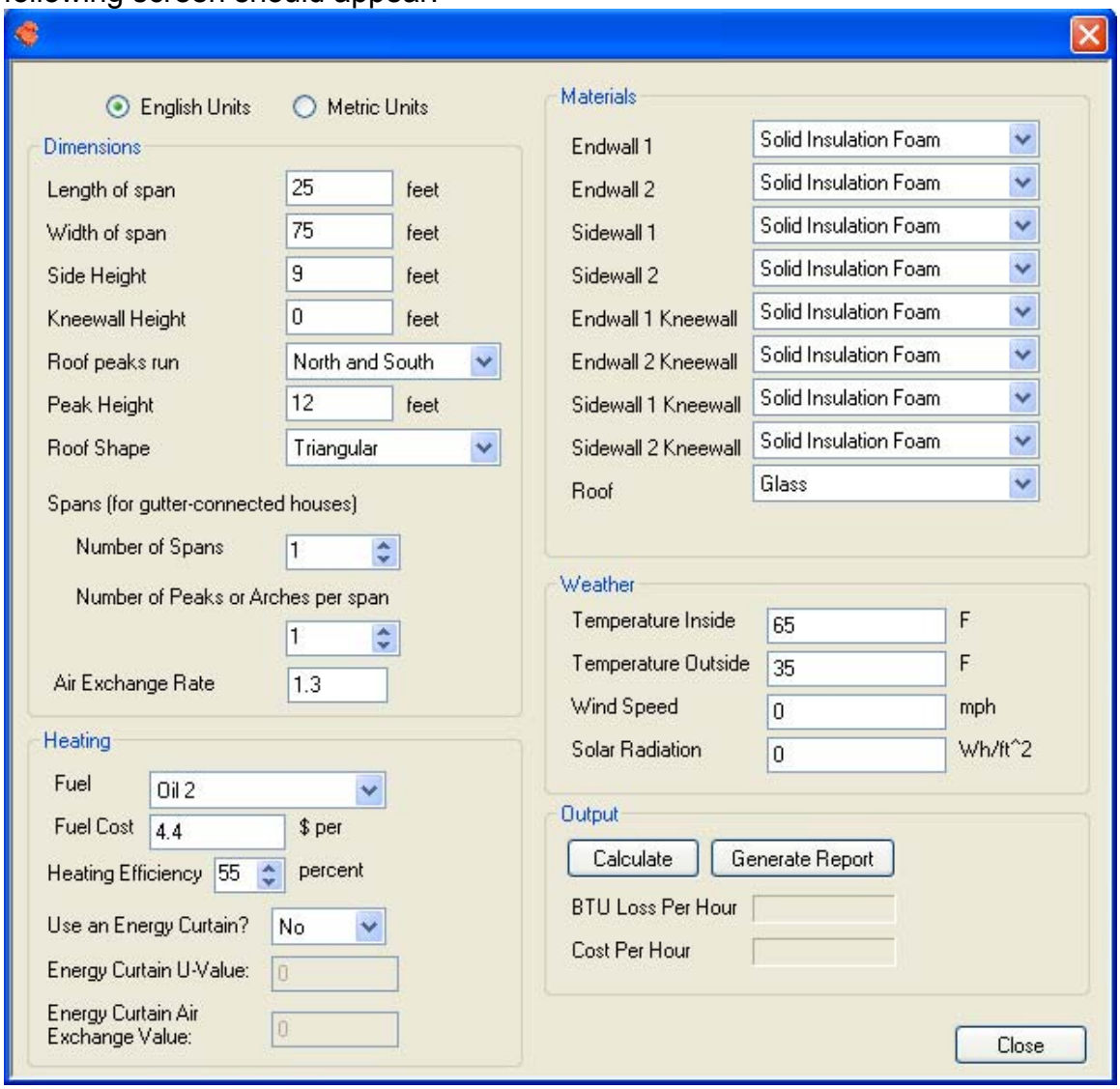
Virtual Grower allows the choice in English or Metric units. In the Options window in the upper left corner, you can choose English or Metric by clicking on or next to your choice of units. This changes the units to that convention throughout the program.



Analysis

This option allows a user to do nearly everything that the rest of Virtual Grower can for a single hour and user-specified weather. This was installed for specific “what-if” scenarios and to give the user more confidence in the generated numbers – that is, does the output make sense given simple, steady environmental conditions outside.

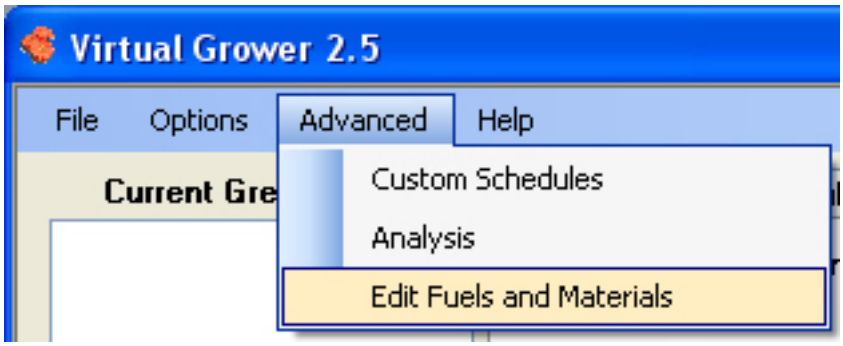
Under the Advanced drop-down menu, choose “Analysis” and the following screen should appear:



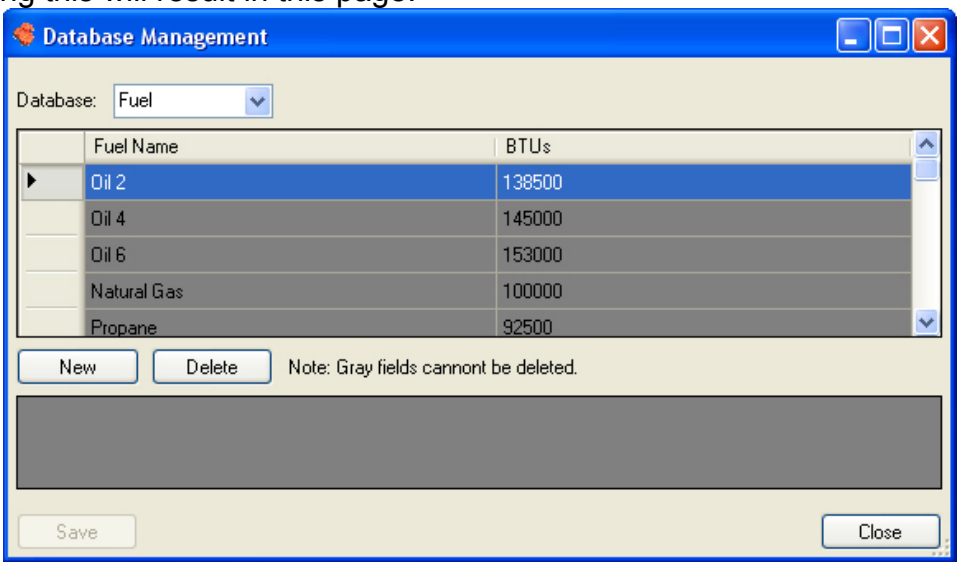
The greenhouse size, material options, fuel features, and output are all similar to the expanded sections. In the Weather box, the user can select the temperature inside, outside, wind speed, and solar radiation, all as constants. When finished, a user can generate and save reports from this section just as in the Cost section in the main program.

Edit Fuels and Materials

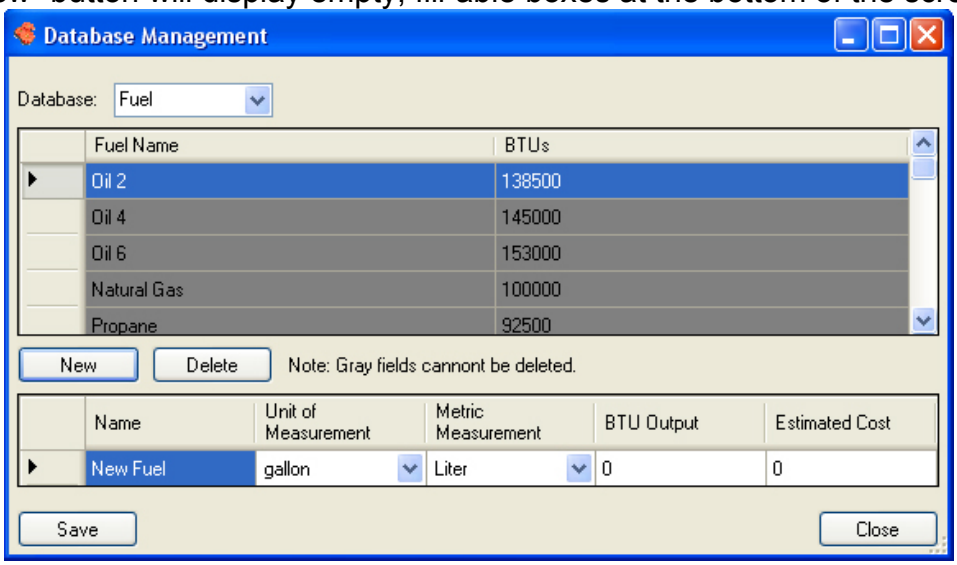
Introduced in version 2.5, a user can now enter and test new fuels and materials. Click on the Advanced option at the top of any page will drop down a list including Edit Fuels and Materials:



Selecting this will result in this page:



Near the top of the screen on the left, you can select the database to modify, with the choice as Fuel or Material. When the database selection is made, clicking on the “New” button will display empty, fill-able boxes at the bottom of the screen:



The user can enter the name of fuel or material and other key information. Clicking on the “Save” button will add the fuel or material to the database, and when the user enters the basic simulation sections, they can use these new fuels or materials in their simulations.

It is impossible to change the basic, pre-programmed fuel and material types included in the software installation.

Help

An electronic version of this manual can be found in the Help window as well as credits, acknowledgements, and other useful references. If you have any questions or comments and can not find the information in this manual or in the About section, feel free to contact us at USDA-ARS@utoledo.edu.

Some Assumptions of Virtual Grower 2.5

Weather at a location

The weather information is not average values for a period of time, but typical or representative values for that date and time. This means that at your location, the month of January used in the program is from 1974 and the month of February is from 1982. Those years were chosen because they represent "typical" months at that location.

An alternative method of calculating a building's heat requirements is the use of a "Heating Degree Day" model. This method bases heat needs on the average temperature during a day. If the average temperature is below 65 F (18 C), heating is required. A list of heating degree days for different locations can be found at www.nrcc.cornell.edu/ccd/nrmhdd.html. The heating degree days that Virtual Grower predicts and this database are in close agreement (typically less than 1%). On some days, however, the heating degree day model predicts no heat is needed when Virtual Grower would predict some heat is needed. For example, assume your greenhouse has a set point of 65 F. If a location (hypothetical) has an average temperature of 65 F, has a 12-h day of 75, and a night time of 55, Virtual Grower would heat the house for 12 hours (during the night) and the heating degree day model would predict no heat is needed.

Greenhouse isolation

Currently, each greenhouse is treated as a stand-alone structure with no shared walls with other houses or structures. This would influence heat loss or gain and potentially have a significant impact on the overall costs of heating your greenhouse ranges.

Humidity

Currently, all calculations are assuming dry air. This assumption greatly shortens the calculation time, but would ignore issues such as latent heat (evaporation and condensation) and changes in humidity outside the greenhouse causing changes inside the greenhouse. In Version 2.0, a multiplier was inserted (see Appendix 5, Heat Gain by Solar Radiation) to account for some of the effect due to evapotranspiration. Still, with a single multiplier, the effect of latent heat is assumed constant.

Errors? Questions? Problems? Suggestions?

Contact us (USDA-ARS@utoledo.edu). This is a work in progress and with your help, we can improve Virtual Grower and it can better suit your needs. Please give us feedback – WE WANT TO HEAR FROM YOU!

Appendix 1: Fuel energy content used in Virtual Grower 2.5

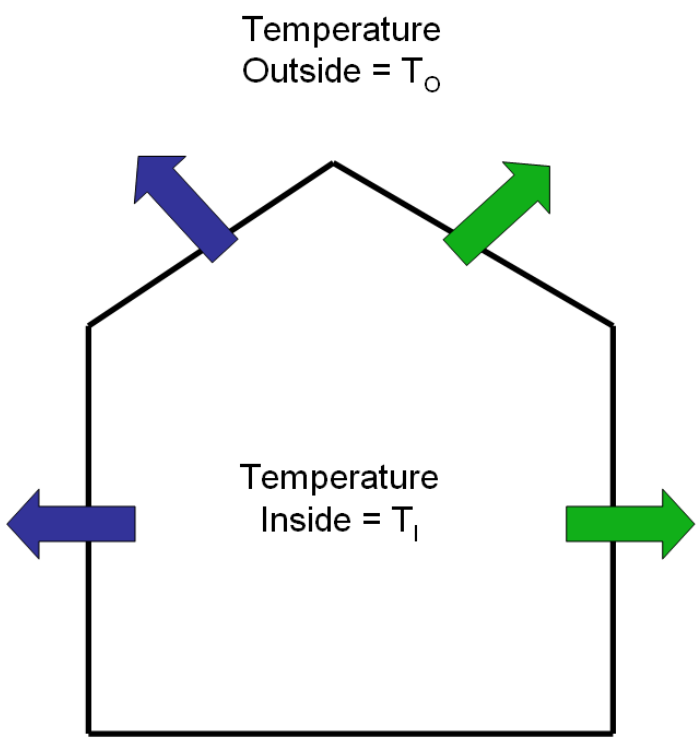
Fuel Type	Energy (btu)	Unit for energetic amount
Fuel Oil #2	138,500	Gallon
Fuel Oil #4	145,000	Gallon
Fuel Oil #6	153,000	Gallon
Natural Gas	100,000	Therm
Propane	92,500	Gallon
Hard Coal	26,000,000	Ton
Soft Coal	24,000,000	Ton
Electricity	3,412	kWh
Methane	1,000	ft^3
Methanol	57,000	Gallon
Landfill Gas	500	ft^3
Butane	130,000	Gallon
Ethanol	76,000	Gallon
Kerosene	135,000	Gallon
Waste Oil	125,000	Gallon
Biodiesel	120,000	Gallon
Gasoline	125,000	Gallon
Soft Wood	12,500,000	Cord
Hard Wood	21,000,000	Cord
Hogged Wood	18,000,000	Ton
Sawdust (green; 45% moisture)	9,000,000	Ton
Sawdust (dry)	16,000,000	Ton
Wood Chips	7,600,000	Ton
Bark	9,750,000	Ton
Wood Pellets (10% moisture)	16,000,000	Ton
Rubber Pellets	33,000,000	Ton
Plastic	19,000	lb
Corn Shells	16,000,000	Ton
Corn Cobs	16,500,000	Ton
Switchgrass	11,625,000	Ton

Values were obtained from Bartok, J.W. Jr., 2005, floriculture fact sheet from U Mass Extension:
http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_fuels.htm

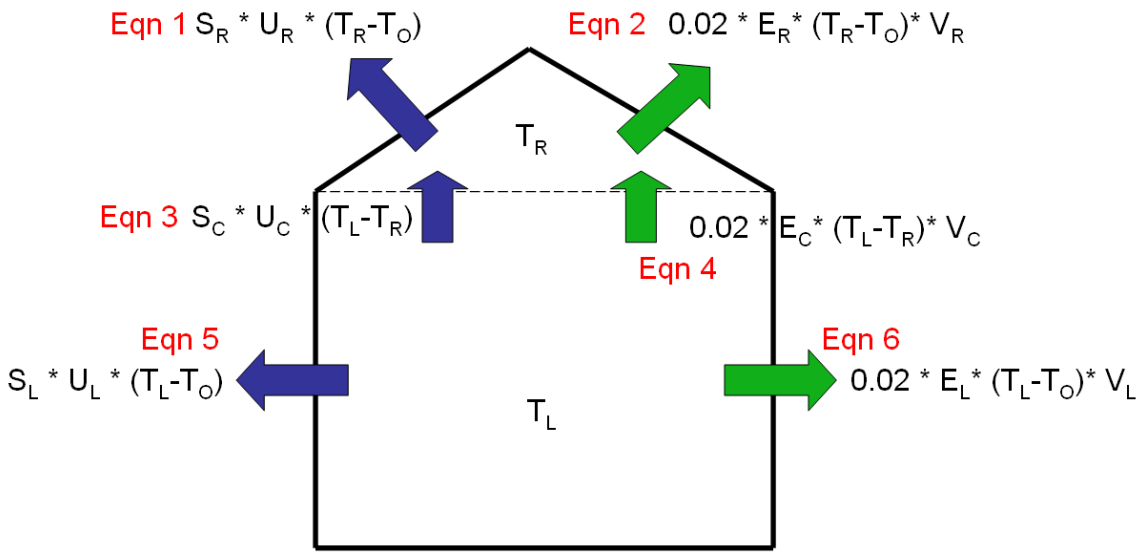
Appendix 2: Energy curtain assumptions

The energy curtain feature of Virtual Grower is an approximation that does not rely on a constant offset or “fudge factor” created by changing the energetic properties of the roof by a constant amount. The impact that a curtain material makes through its inherent insulation value as well as its ability to inhibit air mixing from the upper section to the lower is accounted for in the calculations. To illustrate more specifics on how the curtain calculations were conceived and executed, read the description below.

We have attempted to place a division between the upper and lower sections of a greenhouse in software and treat the greenhouse as two parts if a curtain is in place rather than one greenhouse with different heat loss/gain characteristics. Conceptually, we consider that a greenhouse is losing heat at night from the roof and sides through conduction (blue arrows) and convection (green arrows; for simplicity of the drawing, we show one type of energy loss through a single side of the greenhouse) if the temperature inside (T_I) is less than the temperature outside (T_O).



If an energy curtain is added, the greenhouse is still losing heat from the sides and the roof. However, since the volume of greenhouse above the energy curtain is not actively being heated, there is another heat flow from the lower section to the upper section such that the temperature inside the lower part (T_L) is higher than the temperature of the upper section (T_R).



If T_L is maintained at the setpoint, the temperature in the upper section (T_R) will reach an equilibrium between T_O and T_L, which will depend on T_O, T_L, well as the thermal properties and air exchange of the roof and energy curtain as well as the sizes of the roof and energy curtain. Mathematically, this is:

1) Roof Heat Loss = $[S_R * U_R * (T_R – T_O)] + [0.02 * E_R * (T_R – T_O) * V_R]$
2) Heat Loss over the Curtain = $[S_C * U_C * (T_L – T_R)] + [0.02 * E_C * (T_L – T_R) * V_C]$

When S_R is the surface area of the roof, U_R is the U-value of the roof material, E_R is the air exchanges due to leakage or infiltration through the roof, V_R is the volume of air above the energy curtain, S_C is the surface area of the energy curtain, U_C is the U-value of the energy curtain, E_C is the air exchanges due to leakage or infiltration through the energy curtain, and V_L is the volume of air below the energy curtain. Eqn 5 and 6 in the figure above will be defined later. To get the temperature above the curtain to stabilize, the amount of heat gained through the curtain from the heated greenhouse below and the amount of heat lost to the outdoors must be equal:

3) $[S_R * U_R * (T_R – T_O)] + [0.02 * E_R * (T_R – T_O) * V_R] = [S_C * U_C * (T_L – T_R)] + [0.02 * E_C * (T_L – T_R) * V_C]$

Solve for T_R:

$$[(S_R * U_R * (T_R – T_O)) + (0.02 * E_R * (T_R -T_O) * V_R)] – [(S_C * U_C * (T_L – T_R)) + (0.02 * E_C * (T_L – T_R) * V_C)] = 0$$

$$(S_R *U_R *T_R) – (S_R * U_R * T_O) + (0.02 * E_R * V_R *T_R) – (0.02 * E_R *V_R *T_O) – (S_C * U_C * T_L) + (S_C *U_C *T_R) – (0.02 * E_C * V_C *T_L) + (0.02 * E_C * V_C * T_R) = 0$$

$$(S_R * U_R * T_R) + (0.02 * E_R * V_R * T_R) + (S_C * U_C * T_R) + (0.02 * E_L * V_L * T_R) = (S_R * U_R * T_O) + (0.02 * E_R * V_R * T_O) + (S_C * U_C * T_L) + (0.02 * E_C * V_C * T_L)$$

$$T_R * [(S_R * U_R) + (0.02 * E_R * V_R) + (S_C * U_C) + (0.02 * E_L * V_L)] = (S_R * U_R * T_O) + (0.02 * E_R * V_R * T_O) + (S_C * U_C * T_L) + (0.02 * E_C * V_C * T_L)$$

$$T_R = [(S_R * U_R * T_O) + (0.02 * E_R * V_R * T_O) + (S_C * U_C * T_L) + (0.02 * E_C * V_C * T_L)] / [(S_R * U_R) + (0.02 * E_R * V_R) + (S_C * U_C) + (0.02 * E_L * V_L)]$$

All variables are known or estimated and therefore, T_R can be calculated (see Appendix 3 for U-values of materials). In Virtual Grower, the energy flows are calculated every hour based on the historical database for each location so T_R changes each hour based on the outside temperature (and if there are any custom schedules used for that greenhouse).

TOTAL ENERGY FLOW WITH ENERGY CURTAINS

Once T_R is calculated, hourly heat loss from a greenhouse is the result of the sum of Eqn 1, Eqn 2, Eqn 5 and Eqn 6 (from figure above), where S_L is the surface area of the lower section, U_L is the U-value of the materials on each wall of the lower section, E_L is the air exchange rate of the lower section, and V_L is the volume of the lower section.

CAUTION:

This calculation does not take into account the energy flux from radiation. Energy losses from this component may be significant and could cause the assumptions used in the energy curtain calculations for Virtual Grower 2.5 to over-estimate the impact of having energy curtains. Furthermore, we continue with the assumption of dry air for all air/heat fluxes and do not factor in the impact of heat storage of the ground and materials.

The energy curtain feature is only activated at night, which is based on your location in the country and not by heating schedule. Functionally, the curtain acts as if it instantly snaps shut at sundown then instantly snaps open at dawn.

Appendix 3: U-values for materials

Material	**U-value (Btu hr^{-1} $°F^{-1}$ ft^{-2})**	**Light Transmittance (%)**
Glass	1.13	0.75
Glass double layer	0.65	0.70
Fiberglass	1.00	0.75
Corrugated polycarbonate	1.20	0.75
Polyethylene	1.15	0.65
Polyethylene double layer	0.70	0.60
Polycarbonate bi-wall	0.65	0.60
Polycarbonate triple-wall	0.58	0.56
Acrylic bi-wall	0.65	0.60
IR film	1.00	0.65
IR film double layer	0.61	0.60
Solid insulation foam	0.23	0
Concrete Block	0.51	0
Poured Concrete	0.75	0
Insulated Concrete	0.13	0
Energy Curtains		**Air Infiltration (leakage per hour)**
Mobile air curtain	0.68	1.5
Stationary air curtain	0.54	1.5
White spun bonded polyolefin film	0.51	0.7
Grey spun bonded polyolefin film (light)	0.56	1.5
Clear polyethylene film	0.45	0.4
Black polyethylene film	0.48	0.4
Grey spun bonded polyolefin film (heavy)	0.43	1.0
Aluminum-clear vinyl fabric	0.40	0.7
Aluminized fabric	0.39	0.9
Aluminum-black vinyl fabric	0.63	0.7
Double layer spun bonded polyester	0.53	1.0

Values were obtained from Bartok, J.W. Jr., 2005, floriculture fact sheet from U Mass Extension:
http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_fuels.htm
and Aldrich, R.A. & J.W. Bartok Jr. 1994. Greenhouse engineering. NRAES. Ithaca, NY.

Appendix 4: How the maximum BTU output is calculated

This feature from the Costs tab is designed to assist in boiler or heater sizing. Simply, the value reported is the largest heat loss rate for your greenhouse design, location, and heat schedule.

The program can calculate the heat loss for a greenhouse for every hour in a year or other selected time frame based on your heating schedule. After calculating heat flow for each hour, the largest number is reported. This number is also based on the number of greenhouses selected, so if more than one greenhouse was designed in the design phase, the maximum BTU output reported is assuming if all selected greenhouses are run off a single heater/boiler. When using this feature, remember that the values are based on TYPICAL weather at that location and does not estimate very cold weather events (i.e. a cold snap or inversions). Therefore, you may need to add more BTU to “size up” your boiler for the greenhouse to account for those events. This decision is based on the weather and also the grower’s risk tolerance for extreme weather events.

Appendix 5: Calculating Energy Flow

There are two basic equations that Virtual Grower uses to calculate energy flow through a greenhouse. One is for conduction, the transfer of heat through the structure of the greenhouse, and the second is for convection, the transfer of heat by mixing cooler outside air with warm greenhouse air. When calculating the heat loss for any greenhouse structure, both of these equations are taken into account, at least to some degree.

The particular equations we used are from Aldrich and Bartok, 1994, Greenhouse Engineering, NRAES publication 33, and are outlined below:

Conduction

To calculate conduction over any greenhouse surface, four values are used; the temperatures on either side of the surface (usually the temperature set point of the greenhouse and the current temperature outside), the area of the surface, and a constant known as the U-value of the surface material (See Appendix 3 for U-values). The U-value represents a typical amount of heat energy that will cross a certain area of the material, per degree difference between the inside and outside temperatures. By multiplying these values together, the amount of heat per hour that is lost to that surface can be found. For example, if a small greenhouse was set to 65ºF and the outside temperature was 45ºF, a 100 ft^2 sheet of glass with a U-value of 1.13 BTU/ft^2 -ºF-hour, then the amount of heat lost over the sheet of glass would be:

$$(65ºF - 45ºF) \cdot 100\ ft^2 \cdot 1.13\ BTU/ft^2\text{-}ºF\text{-hour} = 2260\ BTU/hour$$

Lastly, this value can be multiplied by a correction factor to account for the effects of wind. See Appendix 6 for a list of the correction factors used.

Convection

To calculate convection for any particular greenhouse, four values are used; the temperatures on the inside and outside of the greenhouse, the volume of air within the greenhouse, and a correction factor representing the relative leakiness of the greenhouse structure. By multiplying the difference between the two temperatures by the volume and the correction factor, an estimate of heat loss can be obtained. For example, if the temperature outside was 45ºF, the temperature inside was maintained at 65ºF, the volume of the greenhouse was 5000 ft^3 and the greenhouse was assumed to have an average 'leakiness' (correction factor = 0.02 BTU/ft^3-ºF-hour), the amount of heat lost per hour due to convection would be:

$$(65ºF - 45ºF) \cdot 5000\ ft^3 \cdot 0.02\ BTU/ft^3\text{-}ºF\text{-hour} = 2160\ BTU/hour$$

As with conduction, a correction factor to account for the effects of wind can be applied – see Appendix 6.

Totaling Heat Loss

To find an estimate of the heat energy lost for an entire structure, conduction is calculated for each wall, each portion of the kneewall, and for the

roof, and convection is calculated for the whole structure. Adding the results together gives us our estimate.

Heat Gain by Solar Radiation

For every location in Virtual Grower, there is a database of expected solar radiation which can be used to find an estimate of how much heat the greenhouse will gain from the sun. For our estimate, we simply multiply the amount of light energy hitting per square foot of ground space by the total footprint of the greenhouse. Not all the energy from the sun will heat the greenhouse; reflection off the greenhouse surfaces and evapotranspiration will dramatically decrease the amount of energy or heat from the sun. To compensate for this, Virtual Grower assumes that about 33% is reflected from the greenhouse materials and about 50% of the remainder is used for evaporating water from plants and substrate surfaces. This means that only 33% of the sun's energy heats the greenhouse. To estimate heat gain through solar radiation, Virtual grower multiplies that amount of light energy hitting per square foot of ground space, 0.33 (the amount of light making it into the greenhouse), and by the total footprint of the greenhouse.

Net Heat Change in the Greenhouse and Heating Costs

Using the above calculations, Virtual Grower calculates the net amount of heat energy leaving or entering the greenhouse. This is simply done by adding the total heat lost to conduction and convection to the heat gained by solar radiation. If the result is negative, i.e., the greenhouse is cooling off, the number of BTUs lost is assumed to be the number of BTUs added to the greenhouse by its heaters, to keep it at its current temperature. If the number is positive, it is assumed that the greenhouse is being cooled somehow and that no fuel is being burned to heat the structure.

To calculate a cost for heating the greenhouse, the number of BTU's being lost is divided by the amount of heat gained from burning one unit of fuel (whichever fuel is selected), adjusted for the given heater efficiency. This gives us the amount of fuel needed to keep the greenhouse up to temperature. Finally, the cost to heat the structure is calculated by multiplying the units of fuel burned by the cost per unit specified for that greenhouse.

Using Energy Curtains

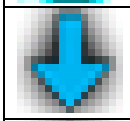
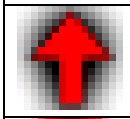
When an energy curtain is being used in a greenhouse, the amount of heat lost to the structure is calculated somewhat differently. Refer to Appendix 2 for an explanation for how this is done.

Appendix 6: Correction factors used in Virtual Grower

Correction factor	Conditions	Value
Wind speed for conduction and convection	wind < 15 mph	1
	15 mph < wind < 20 mph	1.04
	20 mph < wind < 25 mph	1.08
	25 mph < wind < 30 mph	1.12
	30 < wind	1.16

Values were obtained from Bartok, J.W. Jr., 2005, floriculture fact sheet from U Mass Extension:
http://www.umass.edu/umext/floriculture/fact_sheets/greenhouse_management/jb_fuels.htm

Appendix 7: Warnings for plant growth

Symbol	What it means
	Temperature set point is below the minimum temperature or base temperature for this crop and it is likely that the plant will freeze or sustain irreparable chilling injury.
	Temperature set point is warm enough to sustain growth, but growth and development will be slower than what is possible if the plant is grown under optimum temperatures.
	Temperature set point is warm enough to sustain growth, but growth or development will be delayed or suppressed due to too elevated temperatures.
	Temperature set point is above the maximum temperature for this crop and it is likely that the plant will die due to heat stress during production.
	In the current heating schedule, the crop will grow but does not have enough time to reach flowering or maturity. Extending the heating schedule or production time will allow the crop to reach maturity.

Appendix 8: Calculating plant growth and development

Crop growth and development depends in large part on light and temperature. Virtual Grower allows for a great deal of control over temperature and relies on the weather database for light. For the most rapid rate of development, many crops require an inductive photoperiod; without this photoperiod, plants will fail to flower or development will be significantly delayed, yet may continue to grow vegetatively. For simplicity only, we have decided to assume that the photoperiod required for proper development (i.e., flowering) for each crop is being met. Therefore, for Virtual Grower, crop development will only depend on the average temperature and light levels during the cropping schedule. For growth, we have used a single leaf photosynthesis model and allow light to drive growth. In this model, however, leaves must intercept that light in order to grow. Therefore, some estimate of leaf expansion must precede estimates of photosynthesis and biomass gain.

In the following section, more detail is given for the assumptions and calculations for plant development and growth in Virtual Grower. At the end of this section, many references we have found useful are reported, if you would like to go into more detail on crop modeling.

Light

The unit of light that is used for Virtual Grower is the Daily Light Integral or DLI, measured in moles of photons per square meter per day. It is the total or integrated light during one day that a plant can use. The weather database used in this software reports total radiation averaged for each hour, in Watts per square meter. This is converted to photosynthetically active radiation (PAR; units are micromoles of photons per square meter per second) by dividing total radiation by 0.47. The result is converted to moles of photons per square meter per hour by multiplying by a factor of 3600 (seconds per hour) and dividing by a million (number of micromoles in a mole). For a given day, the total in each hour is added together to give us DLI. The light added to a greenhouse from supplemental lighting is added to the DLI calculations, and therefore influences growth and development.

Temperature

Virtual Grower uses average daily temperature to determine aspects of plant growth rather than by instantaneous temperature, day-time temperature, or night time temperature alone. The average daily temperature is calculated by using a weighted average of programmed temperatures (for your programmed heating schedule) and time, in hours, at each temperature.

Calculating Development (Time to flowering)

Each flowering species uses the same general model to predict time to flowering:

$$1/\text{days to flowering} = y_0 + T_1 * temp_{avg} + T_2 * temp_{avg}^2 + Q_1 * DLI + Q_2 * DLI^2 + TQ * DLI * temp_{avg}$$

Where y_0 is the reciprocal of days to flowering when temperature and light are zero, $temp_{avg}$ is the average daily temperature, T_1 is the linear parameter for the effect of $temp_{avg}$ on development, T_2 is the curvilinear parameter for the effect of $temp_{avg}$ on development, Q_1 is the linear parameter for the effect of DLI on development, Q_2 is the curvilinear parameter for the effect of DLI on development, and TQ is the parameter that allows any interactions between DLI and $temp_{avg}$.

Virtual Grower uses unique, empirically derived parameters to fit the above equation to predict development for each of the seven modeled floricultural crops. The structure of the equation above allows for temperature and light to act directly, in non-linear ways, and permits interactions between light and temperature. In most cases, one or more of the parameters are zero. Upon calculating the days to flower, Virtual Grower rounds the number of days to the nearest half-week. The references for the equations used for each species are:

Adams, S.R., S. Pearson, and P. Hadlet. 1997. The effects of temperature, photoperiod, and light integral on the time to flowering of pansy cv. Universal Violet (*Viola* x *wittrockiana* Gams). Annals of Botany. 80:107-112

Armitage, A.M., N.G. Seager, I.J. Warrington, D.H. Greer, and J. Reyngoud. 1990. Response of *Oxypetalum caeruleum* to irradiance, temperature, and photoperiod. J. Amer. Soc. Hort. Sci.

Blanchard, M. and E. Runkle. 2008 (on-going). Temperature and daily light integral effects on crop timing and quality of bedding plants. PhD dissertation, Michigan State University.

Erwin, J, R. Heins, R. Berghage, and B. Kovada., 1990. Temperature effects *Schlumbergera truncata* "madisto" flower initiation. Acta Hort. 272:97-101.

Faust, J.E. and R.D. Heins. 1994. Modeling inflorescence development of the African violet (*Saintpaulia ionantha* Wendl.). J. Amer. Soc. Hort. Sci. 119:727-734.

Frantz, J. M., Ritchie, G., Cometti, N. N., Robinson, J., and Bugbee, B. 2004. Exploring the limits of crop productivity: Beyond the limits of tipburn in lettuce. J. Amer. Soc. Hort. Sci. 129:331-338.

Karlsson, M.G., R.D. Heins, J.E. Erwin, and R.D. Berghage. 1989. Development rate during four phases of chrysanthemum growth as determined by preceding and prevailing temperatures. J. Amer. Soc. Hort. Sci. 114:234-240.

Moccaldi, L.A. and E.S. Runkle. 2007. Modeling the effects of temperature and photosynthetic daily light integral on growth and flowering of *Salvia splendens* and *Tagetes patula*. J. Amer. Soc. Hort. Sci. 132:283-288.

Moe, R. 1983. Temperature and daylength responses in *dianthus carthusianorum* cv. Napolean III. Acta Hort. 141:165-171.

Pietsch, G.M., W.H. Carlson, R.D. Heins, and J.E. Faust. 1995. The effect of day and night temperature and irradiance on development of *Catharanthus roseus* (L.) 'Grape Cooler'. J. Amer. Soc. Hort. Sci. 120:877-881.

Pramuk, L.A. and E.S. Runkle. 2005. Modeling growth and development of celosia and impatiens in response to temperature and photosynthetic daily light integral. J. Amer. Soc. Hort. Sci. 130:813-818.

We are currently working to add more species to future versions of Virtual Grower.

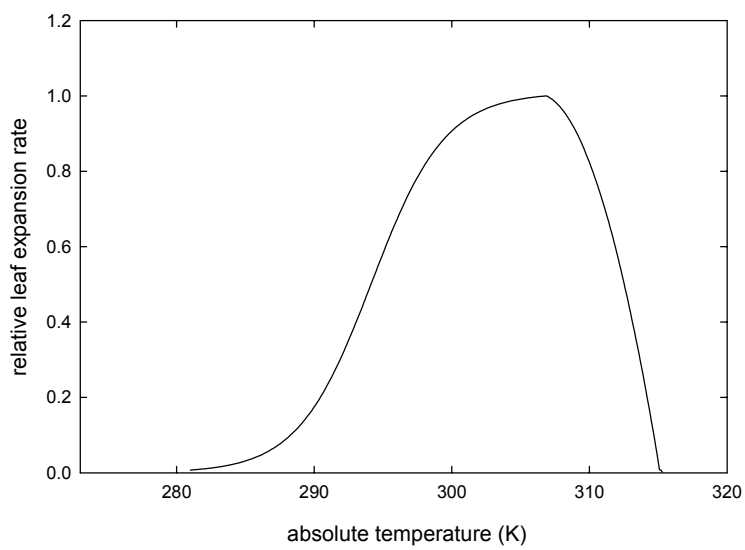
In a typical greenhouse environment, DLI changes daily, but the empirically derived equations are based on laboratory-maintained, constant DLI. Virtual Grower uses the average monthly DLI at the simulated location instead of variable DLI.

Calculating Growth

Leaf expansion

Before a plant can photosynthesize and make use of the available light, that light must be intercepted by a leaf. Therefore, leaf expansion must be considered. The general rate of leaf expansion is assumed to be independent of the species for the sake of simplicity for this model. It is sensitive to average daily temperature, however, and the optimum temperature for this leaf expansion is species dependant, based on a lower-limit to temperature, where possible. If no lower limit for temperature is reported, grower feedback was used to guide us into an approximation for the lower temperature limit for the difference species. The temperature optima (T_{opt}) are then 50°F warmer than that base temperature. Leaf expansion stops at hot temperatures, and that is modeled to be 12°F above the temperature optimum. Each species has a defined T_{opt} and is based on a reported lower-limit for plant growth for that species, where possible. If none is reported, grower feedback was used to guide us into an approximation for the lower temperature limit for the difference species.

The leaf expansion rate has two equations. One equation is used for the temperature from the lower-limit to the temperature optimum and the other is from the temperature optimum to the upper, critical temperature at which expansion stops. Together, these curves yield the following temperature response curve:



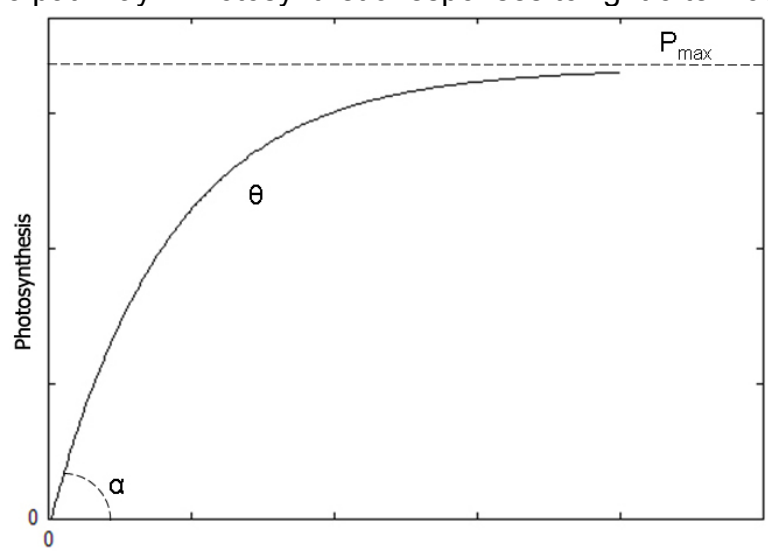
The actual temperature optimum (temperature that gives the largest relative leaf expansion rate) depends on the species.

Photosynthesis

Many excellent models have been published that accurately predict photosynthesis at the single leaf, whole plant, or whole canopy level. Some of these models have been further modified to account for species differences, water availability, humidity, CO_2 concentration, light, nutrition, and photosynthetic pathway, to name a few.

The goal of this component of Virtual Grower was to give a user feedback on how large a plant might be given their management conditions. The actual plant size will vary based on many of the environmental conditions listed above (nutrition, water availability, etc.) as well as starting size of the plant material and pot size. Use the plant size output as feedback on how large or small relative to other environmental settings *within other Virtual Grower simulations* to see the impact on overall plant performance.

The model that is used is based on a commonly used, single-leaf layer model. Selected primarily for its simplicity, the model allows for CO_2. temperature, and light responses, all of which are manipulated in greenhouse production, whereas fertility and water availability are often assumed to be optimal, and the photosynthetic pathway for the vast majority of greenhouse crops is the C3 pathway. Photosynthetic responses to light often look like this:



The initial steepness of the curve (α) depends on things like CO_2 concentration (among other things), the "elbow" of the curve (θ) depends on leaf angle, and the upper limit of the curve (P_{max}) depends on things like light, temperature and CO_2. For a more complete discussion of modeling photosynthesis, we have found the references at the end of this appendix to be useful.

The model's equation is:

$$\text{Photosynthetic rate} = \tfrac{1}{2} \cdot \theta \{\alpha \cdot light_{instant} + P_{max} - [(\alpha \cdot light_{instant} + P_{max})^2 - 4 \cdot \theta \cdot \alpha \cdot light_{instant} \cdot P_{max}]^{1/2}\}$$

Where α is the quantum yield (or photosynthetic efficiency), $light_{instant}$ is the instantaneous light inside the greenhouse at that time, and P_{max} is the maximum rate of photosynthesis theoretically possible.

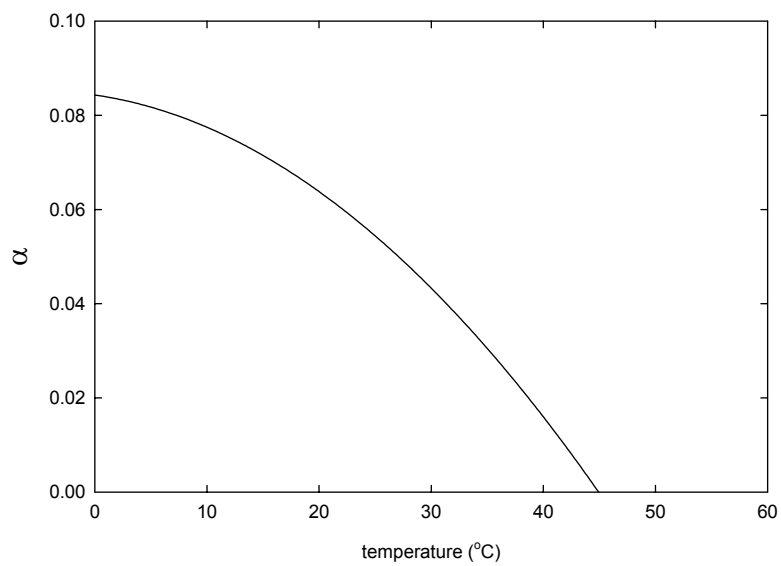
We have made a few simplifying assumptions. θ is defined as 0.8, which is often used for generic plants, P_{max} is set to 100, and α is maximum at 0.084 mol C fixed per mol photons absorbed (this value is open to some controversy, but we have assumed a fairly conservative maximum efficiency for this model; see references for a discussion on this value).

α and P_{max} both respond to temperature and CO_2. These are modeled using the following equations:

α and temperature

$$\alpha = 0.0843 - (0.0003 \cdot \text{current temperature}) - (0.0000341 * \text{current temperature}^2)$$

To yield the following response curve to temperature:



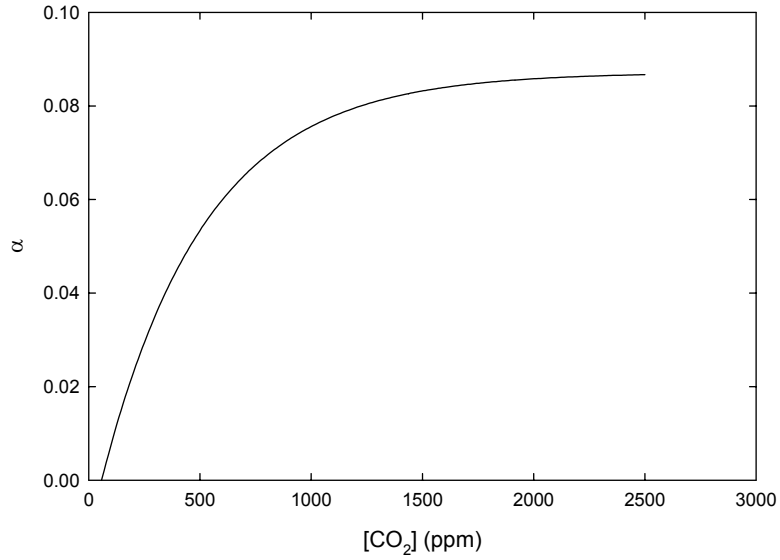
This response is based on Long, (1991), adjusted lower so that maximum α is 0.0843 mol C fixed per mol photons absorbed.

α and CO_2

α responds strongly to the concentration of CO_2 in the air. Current atmospheric CO_2 concentrations are approximately 400 ppm, but optimum photosynthesis for most greenhouse-grown crops occurs at a CO_2 concentration of 1000 to 1200 ppm. Very high CO_2 concentrations (~10,000 ppm) inhibit photosynthesis, but these concentrations are rarely encountered within a greenhouse. The equation Virtual Grower uses to describe the improved efficiency of α is:

$$\alpha = -0.0116 + 0.987 \cdot (1 - e^{(-0.0021*[CO2])})$$

To yield the following response curve for CO_2:

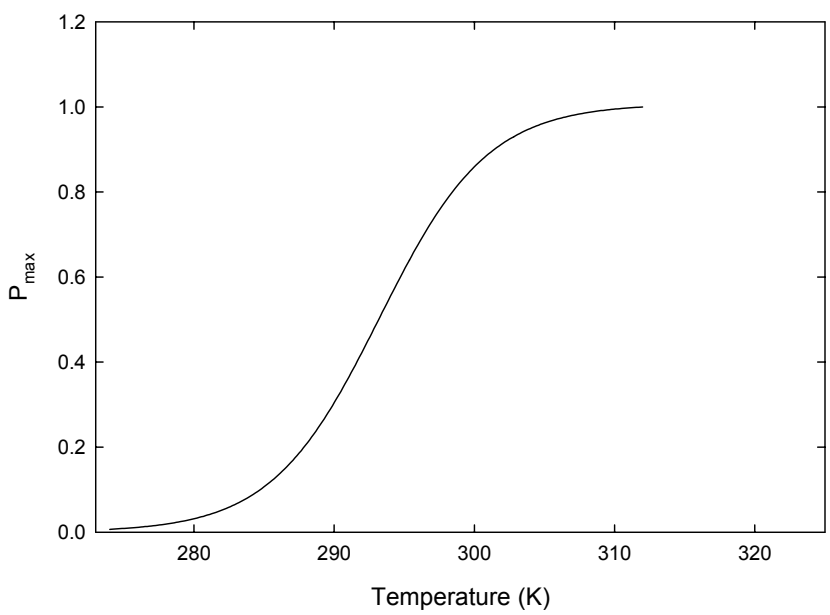


P_{max} and temperature

The maximum rate of photosynthesis depends on temperature and CO_2 and is adjusted, up and down relative to its max value (for this model) of 100 by the following equations:

$$P_{max} = 51.42 / \{1 + e^{[-\text{absolute temperature} - (\text{Tbase}+17)]/4.92}\}$$

To yield the following response curve for temperature:



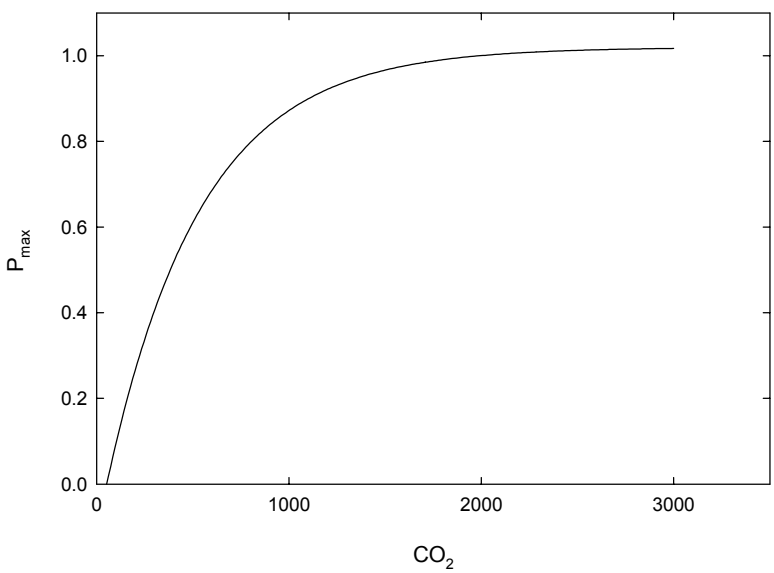
Note that in this equation, P_{max} does not decline in super-optimal temperatures. Sensitivity analysis of this simplifying assumption revealed little changes in overall growth due to the decline of alpha at elevated temperatures as well as decreased leaf expansion at these temperatures.

P_{max} and CO_2

The following equation is used to predict how P_{max} is influenced by CO_2:

$$P_{max} = -0.116 + 1.136 * (1 - e^{-0.002 * [CO2]})$$

To yield the following response curve for CO_2



The final plant size is calculated from a running total of predicted photosynthetic rates for the predicted leaf area exposed to the light environment for every hour during the scheduled interval.

Useful References for Modeling Photosynthesis

Albrizno R, Steduto P. 2003. Photosynthesis, respiration and conservative carbon use efficiency of four field grown crops. Agr. For. Meteor. 116: 19-36.

Alexander, J. D., Donnelly J. R., Shane J. B. 1995. Photosynthetic and transpirational responses of red spruce understory trees to light and temperature. Tree Physiol. 15: 393-398.

Amthor JS. 1989. Respiration and Crop Productivity. Springer-Verlag. New York.

Amthor J. S. 2000. The McCree-de Wit-Penning de Vries-Thornley respiration paradigms: 30 years later. Annals Bot. 86: 1-20.

Amthor JS, Koch GW, Williams JR, Layzell DB. 2001. Leaf O_2 uptake in the dark is independent of coincident CO_2 partial pressure. J. Exp. Bot. 52: 2235-2238.

Atkin OK, Evans JR, Ball MC, Lambers H, Pons TL. 2000. Leaf respiration of snow gum in the light and dark. Interactions between temperature and irradiance. Plant Physiol. 122: 915-923.

Ayari O, Dorais M, Gosselin A. 2000. Daily variations of photosynthetic efficiency of greenhouse tomato plants during winter and spring. J. Amer. Soc. Hort. Sci. 125: 235-241.

Azcón-Bieto J, Lambers H, Day DD. 1983. Effect of photosynthesis and carbohydrate status on respiratory rates and the involvement of the alternative pathway in leaf respiration. Plant Physiol. 72: 598-603.

Azcón-Bieto J, Osmond CB. 1983. Relationship between photosynthesis and respiration. The effect of carbohydrate status on the rate of CO_2 production by respiration in darkened and illuminated wheat leaves. Plant Physiol. 71: 574-581.

Björkman O. 1981. Responses to different quantum flux densities: Plants, light and its effects on photosynthesis. Encyclopedia Plant Physiol. New Series 12: 57-107.

Bugbee B. 1994. Effects of radiation quality, intensity, and duration on photosynthesis and growth. International Lighting on Controlled Environments Workshop. NASA-CP-95-3309.

Cannell M. G. R., Thornley J. H. M. 2000. Modelling the components of plant respiration: Some guiding principles. Ann. Bot. 85: 45-54.

Griffin K. L., Turnbull M., Murthy R., Lin G., Adams J., Farnsworth B., Mahato T., Bazin G., Potasnak M., Berry J. A. 2002. Leaf respiration is differentially affected by leaf vs. stand-level night-time warming. Global Change Biol. 8: 479-485.

Farquhar, G.D., S. von Caemmerer, and J.A. Berry. 1980. A biochemical model of photosynthetic assimilation in leaves of C3 species. Planta 149:78-90.

Funnell KA, Hewett EW, Plummer JA, Warrington IJ. 2002. Acclimation of photosynthetic activity of Zandeschia 'Best Gold' in response to temperature and photosynthetic photon flux. J. Amer. Soc. Hort. Sci. 127: 290-296.

Hammer PA, Tibbitts TW, Langhans RW, McFralane JC. 1978. Base-line growth studies of 'Grand Rapids' lettuce in controlled environments. J. Amer. Soc. Hort. Sci. 103: 649-655.

Hansen LD, Criddle RS, Smith BN, MacFarlane C. 2002. Growth-maintenance component models are an inaccurate representation of plant respiration. Crop Sci. 42: 659.

Jordan, D.B. and W. L. Ogren. 1984. The CO_2/O_2 specificity of ribulose 1,5-bisphosphate carboxylase/oxygenase. Planta 161:308-313.

Lal A, Edwards GE. 1995. Maximum quantum yields of O_2 evolution in C4 plants under high CO_2. Plant Cell Physiol. 36: 1311-1317.

Lambers H, Chapin FS III, and Pons TL. 1998. Plant Physiological Ecology. Springer-Verlag. New York.

Long, S.P. 1991. Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO_2 concentrations: Has its importance been underestimated? Plant Cell Environ. 14:729-739.
McCree KJ. 1974. Equations for the rate of dark respiration of white clover and grain sorghum, as a function of dry weight, photosynthetic rate, and temperature. Crop Sci. 14: 509-514.
McCree KJ. 1982. Maintenance requirements of white clover at high and low growth rates. Crop Sci. 22: 345–351.
Monje O, Bugbee B. 1996. Characterizing photosynthesis and transpiration of plant communities in controlled environments. Acta Hort. 440: 123-128.
Monje O., Bugbee B. 1998. Adaptation to high CO_2 concentration in an optimal environment: radiation capture, canopy quantum yield, and carbon use efficiency. Plant Cell Environ. 21: 315-324.
Monteith, JL. 1977. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London, Series B 281:277−294.
Nemali KS, van Iersel MW. 2004. Light effects on wax begonia: photosynthesis, growth respiration, maintenance respiration, and carbon use efficiency. J. Amer. Soc. Hort. Sci. 129: 416-424.
Norman JM, Arkebauer TJ. 1991. Predicting canopy photosynthesis and light-use efficiency from leaf characteristics. In: Modeling crop photosynthesis-from biochemistry to canopy. CSSA Special Publication 19: 75-94.
Raulier F, Bernier PY, Ung C. 1999. Canopy photosynthesis of sugar maple (*Acer saccarum*): comparing big-leaf and multilayer extrapolations of leaf-level measurements. Tree Physiol. 19: 407-420.
Sanchez CA, Allen RJ, Schaffer B. 1989. Growth and yield of crisphead lettuce under various shade conditions. J. Amer. Soc. Hort. Sci. 114: 884-890.
Sharp RE, Matthews MA, Boyer JS. 1984. Kok effect and the quantum yield of photosynthesis. Light partially inhibits dark respiration. Plant Physiol. 75: 95-101.
Thornley J. H. M., Cannell M. G. R. 2000. Modelling the components of plant respiration: Representation and Realism. Ann. Bot. 85: 55-67.Thornley JHM, Johnson IR. 1990. Whole plant respiration and growth energetics. In Plant and Crop Modeling. pp. 264-285. Clarendon Press, Oxford.
Will RE, Barron GA, Burkes EC, Shiver B, Teskey RO. 2001. Relationship between intercepted radiation, net photosynthesis, respiration, and rate of stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. For. Ecol. Man. 154: 155-163.

Appendix 9: Estimating heating system efficiency

As stated in the general manual, the estimate for heating system efficiency uses general descriptions of a few key features of most heating systems to “dial in” an overall heating system efficiency. The heating efficiency section is based on a matrix of measured and reported values of similar system parts that engineering colleagues have measured or documented in "the field". Virtual Grower uses four components, each with an efficiency of 0 to 100%, in theory. In practice, some of the components have a much more limited range (for example, maintenance ranges from 90 to 100%). As the user selects system components and descriptions that are similar to their system, the individual efficiencies are multiplied together to produce an overall system efficiency.

For example, selecting a Unit heater starts the efficiency matrix at a number, say 85% (a value that is often reported on the sides of heaters or in their manuals and can therefore be entered directly by the user as an override value). Power-vented units are more efficient than typical gravity ventilation, so that component may have a 90% efficiency by itself. Note that these two incorporate to some degree combustion efficiencies. Selecting a heat delivery option of overbench heating with no tube might have an individual efficiency of 60%. Finally, maintenance and age need to be considered, and if the heater is fairly new (3 to 5 years) and has been taken care of reasonably well, “maintenance efficiency” may have about a 95% efficiency. In this example, the system efficiency is 43.6% (85% x 90% x 60% x 95%).

When we originally developed the matrix, we calibrated it to measured efficiencies at a number of greenhouses using many of the listed heating systems. We found "real" life cycle system efficiencies for many of the unit heaters was only around 50%. One of the goals of this matrix is to allow a user to see the impact that each choice makes on the overall system efficiency.

Note that this matrix should be treated as a ballpark estimate only and should not substitute for a licensed engineer to thoroughly evaluate your system. Realizing that we truly do not know some of these numbers, we do 2 things: 1) we allow for a user override and 2) we limit the efficiencies on ventilation and maintenance efficiencies to between 90 and 100% so they do not penalize the overall system too much.

Appendix 10: Calculating lighting costs

The costs per day that are calculated for a greenhouse utilizing supplemental lighting are based on number of lamps, wattage of those lamps, the wattage of the ballasts, hours per day the light is used, and electricity costs in the following manner:

# of lamps * (lamp + ballast wattage) * hours * electricity costs

Remember to convert the lamp wattage to kW since electricity costs are likely in kW-h. For example, in a greenhouse containing 20 400-W lamps running off of 64-W ballasts for 6 hours at an electricity cost of $0.13 per kW-h, the cost per day would be:

20 lamps * [(400 W + 64 W)/1000] * 6-h * $0.13 kW-h = $7.24

This calculation is based on the example provided in:
Fisher, P. and A.J. Both. 2004. Supplemental lighting technology and costs. From Lighting Up Profits, Edited by P. Fisher and E. Runkle. Meister Media Worldwide, Willoughby, OH.
In Virtual Grower, each of these parameters can be set, and the hours the lamps are activated can be variable depending on the weather and threshold settings.

The type of lamp selected is important when lighting units are changed, and in the use of light provided at plant level to calculate DLI in the plant growth and development sections. The conversions the Virtual Grower uses are summarized in the table below:

Unit	High Pressure Sodium	Metal Halide	Cool White Fluorescent	Incandescent
footcandles	1	1	1	1
lux	10.76	10.76	10.76	10.76
$\mu mol\ m^{-2}\ s^{-1}$	0.13	0.15	0.15	0.22
$W\ m^{-2}$	0.026	0.033	0.032	0.043

This table is adapted from the version presented in:
Fisher, P. and E. Runkle. 2004. Managing lighting in the greenhouse – why is it important? From Lighting Up Profits, Edited by P. Fisher and E. Runkle. Meister Media Worldwide, Willoughby, OH.