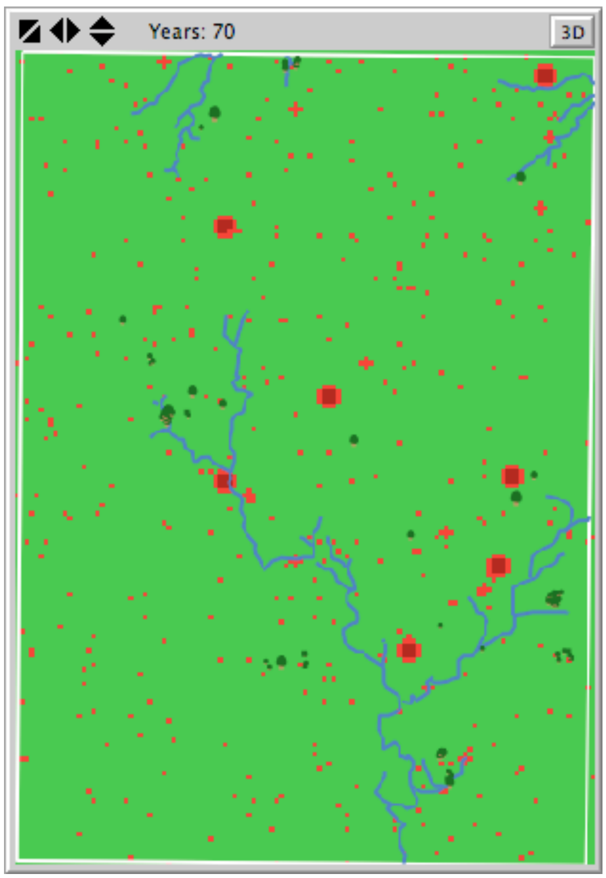
USER MANUAL

for the

BIG-LEAF MAHOGANY GROWTH & YIELD MODEL



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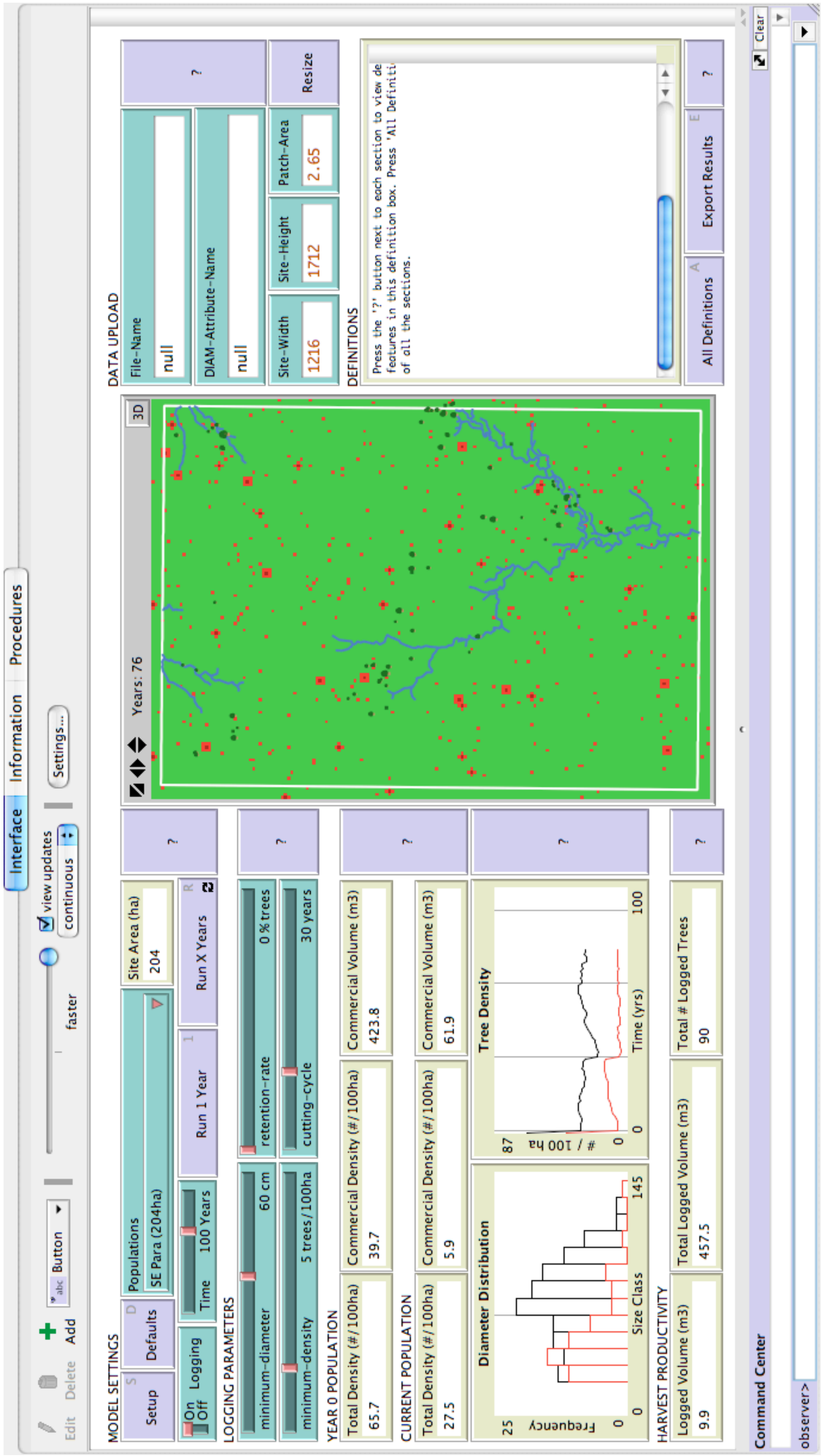
On the cover: A big-leaf mahogany population (204 hectares) in southeast Pará after 70 years of simulation. Dark circles represent mahogany trees, sized according to diameter. The red squares represent disturbances with the darker red portions representing the zone of recruitment. Seasonal streams are shown in blue and the site boundary is shown in white.



Model Schematic. The model interface as it appears when installed on your computer.

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1 MODEL INTRODUCTION

In recent decades big-leaf mahogany, *Swietenia macrophylla*, has been intensively harvested across its natural range in tropical South America. Future timber production from natural forests will depend on protection and stewardship of surviving commercial populations through sustainable management practices. The Big-Leaf Mahogany Growth & Yield Model presented here projects population recovery and timber production from simulated harvests of mahogany in the Brazilian Amazon. The model offers forest managers a computer-based tool for assessing the impact of current management practices on both pre-installed example mahogany populations and on user-entered populations. Although the model was developed based on mahogany population dynamics in Brazil, it can offer useful insights into post-harvest recovery by natural populations throughout South and Central America. The growth & yield model uses the NetLogo 4.1.3 (Wilensky 1999) platform and can be installed on computers using Windows or Mac OS X operating systems.

The growth & yield model functions (algorithms) are derived from demographic data collected annually during 1995–2010 for nearly 600 mahogany trees and many thousands of seedlings, saplings and pole-sized trees at multiple field sites in southeast Pará and Acre. Model simulations can be run with or without harvesting. Under logging scenarios, the model harvests (kills) trees at specified intervals. During intervals between harvests, surviving individuals grow, reproduce, and die at rates observed in field studies. Harvest simulations are based on current legal management practices (60 cm minimum diameter cutting limit, 20% commercial-sized tree retention rate, minimum 5 commercial-sized trees / 100 ha retention density, 30-year cutting cycle). Forest managers can input mahogany population data from field inventories in order to project recovery and production outcomes following multiple harvests. Harvest parameters can be changed to view population and timber production outcomes under alternative management scenarios by adjusting one or more of the four management practices.

The model interface allows harvest simulations to be set up and run by clicking on a series of buttons as explained in the sections to follow. For a given starting population and harvest scenario, each 'run' will yield a different outcome (number of trees and commercial volume harvested, surviving density, etc.). This occurs because the model functions for survival, growth, and reproduction are recalculated each year using a random error term, leading to different long-term outcomes. For this reason, average outcomes from multiple simulations will best represent long-term population recovery and production rates for a given population and harvest scenario.

During each time step (year) of model simulation, the following actions occur on the model interface: (1) the time display advances 1 year; (2) trees grow in size on the landscape (trees are sized according to diameter); (3) trees are logged and removed from the landscape at specified harvest intervals; (4) trees die and are removed from the landscape; (5) the landscape experiences disturbance (red circles = disturbance; dark red = zone of recruitment); (6) trees reproduce and new seedlings are added to the landscape; and (7) disturbances are removed from the landscape and the plots and monitors are updated.

2 MANUAL GUIDE

This User Manual is intended for both beginning and advanced users working with the Big-Leaf Mahogany Growth & Yield Model to inform management decisions. The Manual can be read from front to back for a thorough understanding of how the model works. It can also be queried with specific questions using the section guide below.

MODEL INSTALLATION (**section 3**) details the model installation process.

HELP BUTTONS (**section 4**) explains where to find help while working in the model interface.

A BRIEF GUIDE (**section 5**) provides basic instructions for navigating the model interface.

MODEL SETTINGS (**section 6**) describes example populations available for simulations and how to setup and run the model.

LOGGING PARAMETERS (**section 7**) explains how to adjust the four logging parameters that determine how the model harvests and grows a population over multiple cutting cycles.

SIMULATION RESULTS (**section 8**) describes the monitors and charts on the model interface that track harvests and populations during simulations.

USER DATA UPLOAD (**section 9**) provides instructions for uploading user data into the model framework.

EXPORT SIMULATION RESULTS (**section 10**) explains how simulation results can be exported to text files for analysis and synthesis.

SIMULATION EXPERIMENTS: BehaviorSpace (**section 11**) provides directions for running repeat simulations of a single harvest regime or multiple simulations of varied harvest regimes.

ADVANCED USERS & NETLOGO RESOURCES (**section 12**) reviews the advanced NetLogo features and identifies resources for interested users to learn more about NetLogo programming.

The remaining sections review model features in greater detail and can be read in advance or when specific questions arise. If you still have questions after reading this User Manual, or have any feedback on the model, please contact the authors (**section 17**).

3 MODEL INSTALLATION

3.1 Web Installation

The following section explains how to install the NetLogo software from the 'Big-Leaf Mahogany in Brazil & South America' website and how to run the model using the software.

Step 1. Download Model Package from Website

Please visit our website to download the growth & yield model and to learn more about our research: http://www.swietking.org

The model can be downloaded from ***THE MODEL*** page on the website (http://www.swietking.org/model-applet.html). Download the zip-file appropriate for your operating system (Windows, Mac OS X, or Linux). The zip-file contains the files necessary to install the NetLogo software and run the model on your computer. Left-click on the link to download the file to your default download location. To specify a different download location, right-click on the link and select the *Download Linked File As* option.

Step 2. Unzip Model Package Contents

The contents of the model zip-file must be unzipped using built-in zip software. On most operating systems, double-clicking the zip-file accesses the zip software. However, some systems may require you to right-click the zip-file and select the 'unzip' or 'uncompress' options. Follow the unzip instructions for your software and extract the *Model* folder anywhere on your computer.

Step 3. View the Model Folder Contents

If you successfully unzip the zip-file, you will see the *Model* folder. This folder contains all the files necessary to install the NetLogo software and run the growth & yield model. Double-click the *Model* folder to view its contents. It contains seven elements:

(1) *Growth & Yield Model* file
(2) *Installation Guide* file
(3) *User Manual* file
(4) *NetLogo* folder
(5) *Data* folder
(6) *User* folder
(7) *Results* folder

The *Growth & Yield Model* file is the NetLogo file (.nlogo) containing the growth & yield model. This file will only run after installing the NetLogo software.

The *Installation Guide* file gives instructions on installing the NetLogo software and the Growth & Yield Model. It is identical to ***MODEL INSTALLATION*** in the User Manual (**section 3**).

The *User Manual* file is the User Manual for the Big-Leaf Mahogany Growth & Yield Model.

The *NetLogo* folder contains the NetLogo 4.1.3 installer necessary for your operating systems. This folder also contains the *NetLogo 4.1.3 User Manual* written by the NetLogo design team.

The *Data* folder contains all the data files necessary to run the growth & yield model. NEVER ALTER OR REMOVE ANY FILES IN THIS FOLDER.

The *User* folder contains example user upload files. These files should be viewed as templates when uploading your own data into the model framework. You will place your data files in this folder when uploading your own tree data (**section 9**).

The *Results* folder is the recommended destination for all results exports and is the default destination for certain BehaviorSpace simulation results (**sections 10 & 11**).

Step 4. Install NetLogo 4.1.3

Double-click on the *NetLogo* folder to view its contents.

If you are using a **Windows** computer, double-click the *NetLogo4.1.3Installer.exe* installer file.
If you are using a **Mac OS X** computer, double-click the *NetLogo 4.1.3.dmg* installer file.
If you are using a **Linux** computer, double-click the *netlogo-4.1.3.tar.gz* installer file.

The installer file will open when double-clicked. Follow the installation instructions to install the NetLogo software on your computer.

If you would prefer to download the NetLogo software from the NetLogo website, download NetLogo 4.1.3 here: http://ccl.northwestern.edu/netlogo/4.1.3/

DO NOT USE ANY OTHER VERSION OF NETLOGO. THE MODEL ONLY WORKS IN NETLOGO 4.1.3. Refer to the *NetLogo User Manual 4.1.3* if you require additional assistance.

Step 5. Open Model NetLogo File

If you have successfully installed the NetLogo 4.1.3 software on your computer, you are ready to open the *Growth & Yield Model* file. Double-click the *Growth & Yield Model* file to begin using the growth & yield model on your computer.

If you use Mac OS X, a blank NetLogo file may open instead of the *Growth & Yield Model* file. This is a known Mac OS X – NetLogo bug and may commonly occur on your computer. It is easily resolved: simply leave the blank NetLogo file open and double-click the *Growth & Yield Model* file again. This will always open the *Growth & Yield Model* file correctly.

3.2 Online Model

The online version of the Big-Leaf Mahogany Growth & Yield Model can be accessed from the following website: http://www.swietking.org/model-applet.html. The online model is identical to the computer model except that it cannot: (1) upload user data files; (2) export simulation results; (3) run **BehaviorSpace** experiments; (4) follow instructions from the **Command Line**; or (5) resize the landscape elegantly.

The online version of the model cannot upload user data or export simulations because of the limitations of our web server. **BehaviorSpace** experiments and **Command Line** queries can only be accommodated by installing and running NetLogo on your computer. The online applet only runs the features kept on the model interface. It does not support any NetLogo services occurring outside the interface.

The interface landscape can be resized in the online version of the model but this feature is more difficult to manipulate online than on your computer. The online model will not resize the landscape to a new **Patch-Area** if the blinking mouse-cursor is still in the **Patch-Area** input. Click anywhere within the online interface to remove the blinking mouse-cursor from the input (clicking in another input is an effective strategy) and click **Resize** to resize the model landscape.

These issues will be resolved if possible. Please sign up to receive updates on the model and our research on our website: http://www.swietking.org

Java Versions

The Big-Leaf Mahogany Growth & Yield Model applet requires that your web browser support *Java 5* or higher. The correct version of *Java* can be obtained following these directions:

- Windows users (Vista, XP, or 2000) can download the *Java* browser plug-in from here: http://www.java.com/en/download/windows_manual.jsp
- Mac OS X users require version 10.4 or higher. No plug-in is necessary.
- Linux and Unix system users need the *Sun Java Runtime Environment Version 5* or higher. This is available for download here: http://www.java.com/. Check your browser's homepage for more information on installing the *Java* plug-in.

If you think you have the right browser and plug-in but the online model still does not work, check your browser's preferences to ensure that *Java* is enabled.

The following website may be helpful for determining which version of *Java* you have and for getting the correct version installed and running: http://www.javatester.org/

Browser Memory

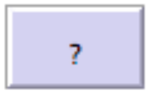
The Big-Leaf Mahogany Growth & Yield Model applet may require more memory than the browser normally makes available. This is more likely to happen when simulating large populations.

On Windows, you can increase the available memory ('heap') space in the *Java Control Panel*'s applet runtime settings. In the *Java* tab of the *Java Control Panel*, view the *Java Applet Runtime Settings*. Enter the following in the *Java Runtime Parameters* field: *-Xmx1024M*. Include the initial hyphen ('-') but not the final period ('.'). More information is available here:

http://download.oracle.com/javase/1.5.0/docs/guide/deployment/deployment-guide/jcp.html

Mac OS X 10.4 users should note that Mac OS X 10.4 initially had a low memory limit for *Java* applets (~64 megabytes). A *Java* update from Apple raised the memory limit to 96 megabytes. This update is available through the *Software Update* but no other options for increasing the *Java* memory limit are available.

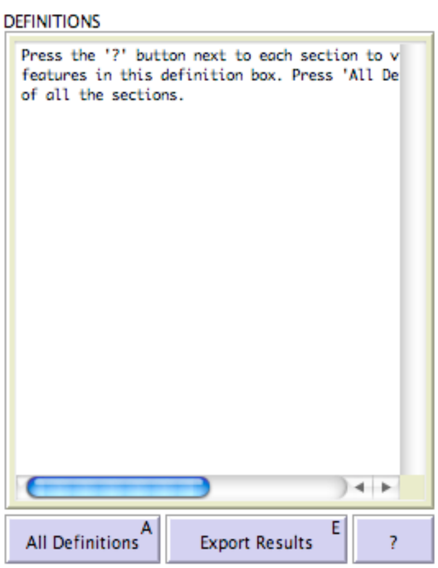
4 HELP BUTTONS



Pressing **HELP** buttons (**?**), located on the right side of each model interface section, allows you to see definitions of model features in the **DEFINITIONS** box (see below). Each model section can be queried in this way.

To see definitions of all model features without pressing each **?** button, press the **All Definitions** button located below the **DEFINITIONS** box. In addition, definitions are listed in ***APPENDIX B: MODEL DETAILS & DEFINITIONS*** (**page 56**) of this Manual.

You can also look for help by selecting **Help** in the NetLogo menu bar. The **Search** option can direct you to specific menu items or help topics. The **Look Up In Dictionary (F1)** option opens a web browser with the dictionary entry for the selected code. The **NetLogo User Manual** and **NetLogo Dictionary** links will open the manual and dictionary in a web browser. The **NetLogo Users Group** option will link you to the NetLogo Users Group, also in a web browser.



This is the **DEFINITIONS** box as it appears on the model interface. Feature definitions can be viewed by using the blue bar to scroll across the text content.

All definitions can be accessed by pressing **A** on the keyboard. This is the shortcut for the **All Definitions** button.

Button shortcuts are displayed in the upper-right corners of the buttons. **E** is the shortcut for the **Export Results** button, **S** is the shortcut for the **Setup** button, **D** is the shortcut for the **Defaults** button, etc.

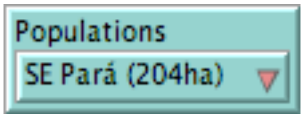
A button shortcut will appear **black** when enabled and **gray** when disabled. To enable shortcuts, click anywhere in the white background of the model interface.

Additional questions can be directed to the authors listed at the end of the Manual (**section 17**).

5 A BRIEF GUIDE

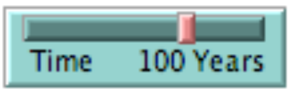
The following guide describes the most basic method for simulating a pre-defined big-leaf mahogany population.

Step 1. Designate Initial Population to Simulate



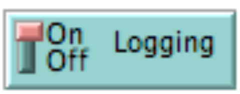
Select either a pre-defined example population or upload your own data using one of the ***USER DATA UPLOAD*** options (**section 9**).

Step 2. Set Simulation Time Limit

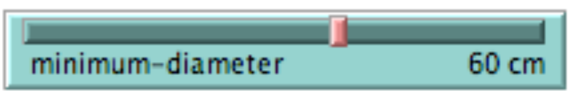


A simulation will end when the time limit is reached or when all the trees are harvested or die. Adjust the time limit by using your computer cursor to slide the red bar horizontally across the dark green slider. Movements to the right increase the parameter values while movements to the left decrease the parameter values.

Step 3. Set Logging Parameters

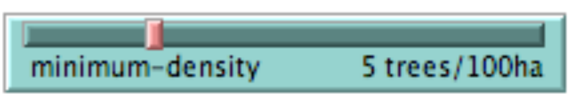


To simulate the population with a harvest regime, select logging 'On', otherwise select logging 'Off'. If logging:



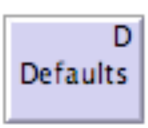
Set a minimum diameter cutting limit (default = 60 cm diameter)

Set a commercial tree retention rate (default = 20% commercial retention)



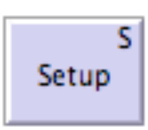
Set a minimum post-harvest commercial population density (default = 5 trees / 100 ha)

Set a cutting cycle length (default = 30 years)



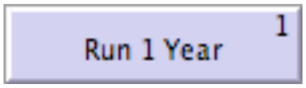
Default harvest parameters can be restored using the **Defaults** button in the upper left-hand corner of the model interface. This button also restores default model settings. Default conditions are reviewed below (**sections 6.2 & 7**).

Step 4. Setup Initial Population

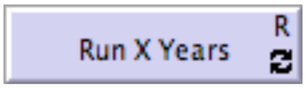


Establish the initial population on the landscape. The population will appear on the model interface in the 'landscape' (middle) field. The landscape population can be resized using the **Patch-Area** input and the **Resize** button (**section 6.1**).

Step 5. Begin Simulations



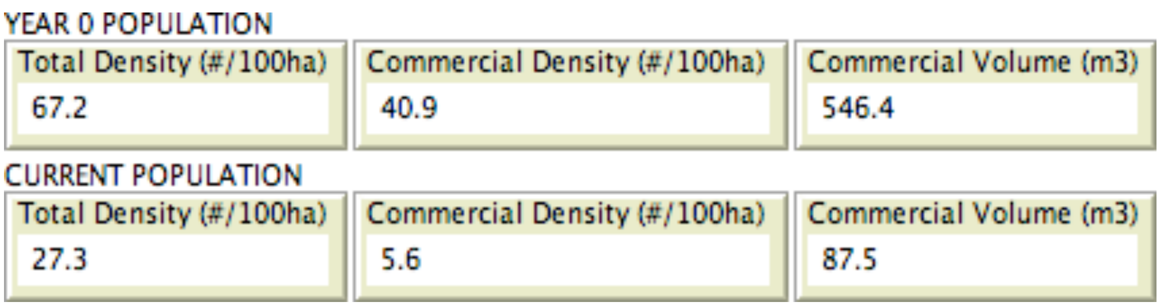
Run the simulation for a single year. This feature is useful when carefully monitoring a simulation or when troubleshooting.



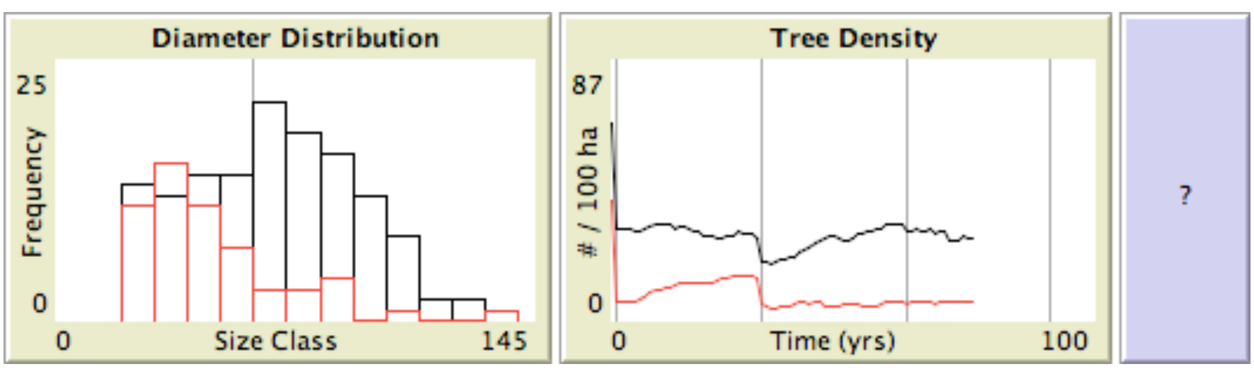
Run the simulation until the time limit is reached, or until all trees are harvested or die, if this occurs before reaching the time limit.

Step 6. Monitor Simulations

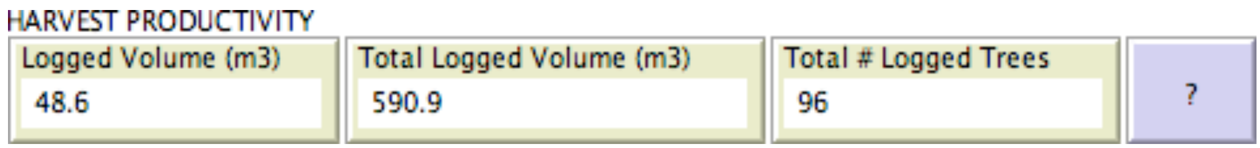
Year 0 Population and **Current Population** monitors report total tree density (trees ≥ 20 cm diameter / 100 ha), commercial-sized tree density (commercial trees / 100 ha), and commercial-sized tree volume (m^3) during **Year 0** and the **Current** simulation year.



Current Population plots show changes in tree size-class distribution and density (trees / 100 hectares) over time. These plots are updated each year according to simulation results. The **Diameter Distribution** plot shows the initial size-class distribution in **black** and the current year size-class distribution in **red**. The vertical **gray** line divides non-commercial and commercial trees. The **Tree Density** plot shows the density of all trees ≥ 20 cm diameter (trees / 100 hectares) in **black** and the density of commercial-sized trees in **red**. The vertical **gray** lines indicate the harvest years, that is, 1, 31, 61, and 91 years in the example shown.



Harvest Productivity monitors report the volume of trees logged in the most recent harvest as well as the number and volume of trees logged in all previous harvests. Monitors are updated after each logging event. **Logged Volume** reports the volume (m^3) of trees logged in the most recent harvest. **Total Logged Volume** reports the volume (m^3) of trees logged in all previous harvests. **Total # Logged Trees** reports the number of trees logged in all previous harvests.

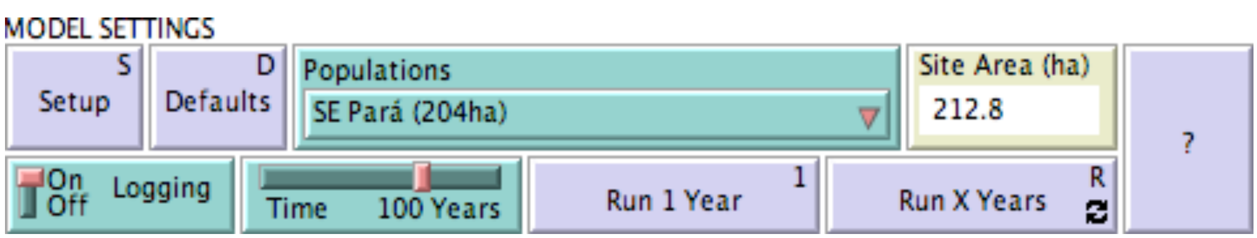


Step 7. Export Simulation Results

Export the simulation results to a text (.txt) file on your computer. Results describe initial and final populations and harvest productivity.

6 MODEL SETTINGS

The **MODEL SETTINGS** parameters determine: (1) which population is simulated during model runs; (2) whether logging is performed; and (3) how long the simulation is run. The **MODEL SETTINGS** buttons set up the initial population, re-set parameters to default conditions, and begin model simulations. The area (in hectares, or ha) of the field site is also displayed in this section.



6.1 Setup & Resize Initial Population

The **Setup** button establishes the initial population on the model landscape shown across the center of the model interface. The population displayed on the landscape is selected from the **Populations** menu, which lists three pre-defined example populations and three user-defined population upload options.

The example populations are based on mahogany population and spatial data from study sites in southeast Pará and Acre, Brazil. The user populations represent the three methods for uploading user data into the model. The six population options are summarized below. User populations are discussed in greater depth in ***USER DATA UPLOAD*** (**section 9**).

EXAMPLE POPULATIONS

SE Pará (204ha)	204-ha field site with 158 trees
SE Pará (1035ha)	1035-ha field site with 745 trees
Acre/West Amazon	685-ha field site with 81 trees

SE Pará (204ha) and **SE Pará (1035ha)** present spatial and diameter data for mahogany populations in southeast Pará, Brazil. The forest management and long-term research site, called Marajoara, is located 34 km northwest of Redenção. Marajoara was selectively logged for mahogany during 1992–1994. The population in 204 ha is from a 100% inventory for mahogany trees ≥ 20 cm diameter. The population in 1035 ha contains the 204-ha population but at lower sampling resolution, representing > 80% of trees ≥ 20 cm diameter in this larger forest area. Most of the trees presented here are logged stumps. For more details see Grogan *et al*. references (**section 16**).

Acre/West Amazon presents spatial and diameter data for a mahogany population located 40 km south of Sena Madureira in the western Brazilian state of Acre. This data is from a 100% inventory in 685 ha for mahogany trees ≥ 20 cm diameter. At the time of inventory this was an unlogged population. The low landscape-scale density is typical of western Amazonian mahogany populations.

USER POPULATIONS

User Population (xyd)	upload spatial and diameter data from a spreadsheet
User Population (shp)	upload spatial and diameter data from a shapefile
User Population (csv)	upload non-spatial diameter data from a spreadsheet

The site is drawn in the 'landscape' (middle) field of the model interface. If the site is drawn too small for the available space, increase the value shown in **Patch-Area** and press the **Resize** button (upper-right on interface). If the site is drawn too large for the available space, decrease the value shown in **Patch-Area** and press the **Resize** button. Continue to make adjustments by increasing or decreasing the **Patch-Area** until you are satisfied with the size of your site on the interface. See **section 9.1 Step 4** for more details.

6.2 Setup & Run Simulations

The **Logging** and **Time** parameters determine how the model will simulate the initial population. The **Logging** switch determines whether the population is simulated with or without logging. Select **On** to run simulations with logging. Select **Off** to run simulations without logging.

The **Time** slider determines how long the simulation will run. The model will simulate the growth and harvest of the initial population until the time limit is reached or until all trees are harvested or die, whichever happens first. Population growth and harvests can be simulated up to 150 years. Changes to the simulation length can be made in 5-year increments.

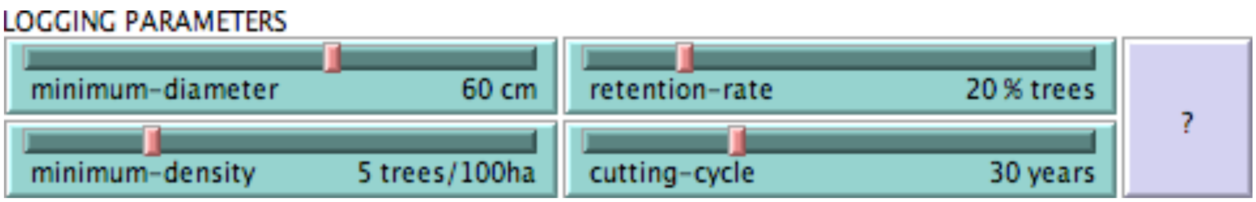
The **Run 1 Year** button runs the model for a single year. The **Run X Years** button runs the model until the time limit is reached or until all trees are harvested or die.

The **Defaults** button returns all variables to default conditions:

Populations	SE Pará 1 (204 ha)	**Logging**	On
Patch-Area	2.75 pixels	**Time**	100 years

7 LOGGING PARAMETERS

The default harvest parameters are set according to current Brazilian forest management regulations for mahogany. These regulations mandate a minimum diameter cutting limit of ≥ 60 cm, the retention of ≥ 20% of commercial-sized trees, the prohibition of logging in areas with population densities ≤ 0.05 trees ha^{-1} (5 commercial trees / 100 ha), and a cutting cycle of 25–30 years.



Harvest parameters can be changed according to user preference. Each parameter can be reset using the computer cursor to move the red bar across the green slider. Movements to the right increase the parameter values while movements to the left decrease the parameter values. The minimum value, maximum value, and value increment are listed for each parameter below:

Minimum Diameter	0 – 100 cm; 5-cm increments
Retention Rate	0 – 100% retention; 5% retention increments
Minimum Density	0 – 20 trees / 100 ha; 1 tree / 100 ha increments
Cutting Cycle	0 – 100 years; 5-year increments

Pressing the **Defaults** button will return the logging parameters to default conditions.

Minimum Diameter	60 cm	**Minimum Retention**	20% trees
Minimum Density	5 trees / 100 ha	**Cutting Cycle**	30 years

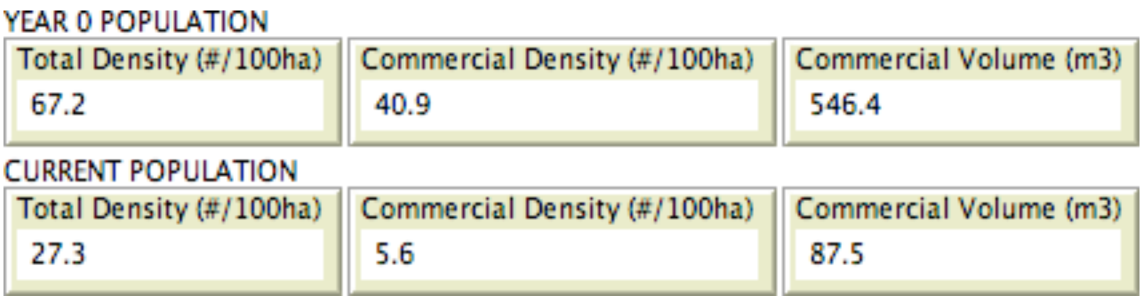
If you do not want to simulate logging, turn logging off using the **Logging** switch discussed above.

8 SIMULATION RESULTS

The model interface provides information to allow users to observe simulations as they progress.

8.1 Population Monitors

The **YEAR 0 POPULATION** and **CURRENT POPULATION** monitors report total tree density, commercial tree density, and commercial tree volume during year 0 and the current simulation year, respectively. **YEAR 0 POPULATION** monitors are static, while **CURRENT POPULATION** monitors are updated each year according to simulation results.



Density monitors report tree density as the number of trees per 100 hectares. Density can be converted to abundance using the following equation:

$$Abundance = Density * (Area / 100)$$

where density (trees / 100 ha) is either total or commercial density and area (ha) is the **Site Area**, as reported in the upper-right portion of the **MODEL SETTINGS** section of the model interface.

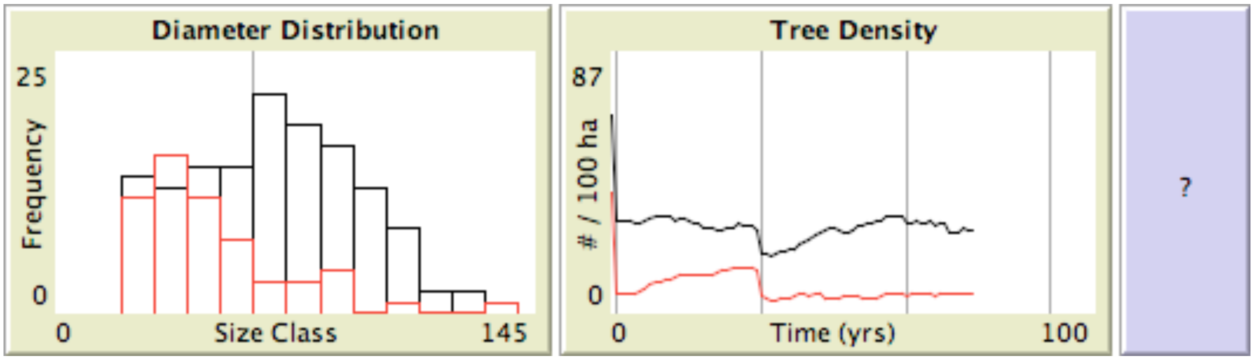
Volume monitors report volume in cubic meters (m^3). Volume is calculated from the diameter of each tree according to the equation:

$$Volume\ (m^3) = -5.297672 + (0.1263387 * Diameter)$$

where tree diameters (cm) are measured 1.3 m above the forest floor or at least 30 cm above the reach of the tallest buttress (Kometter 2011).

8.2 Population Plots

The **CURRENT POPULATION** plots show changes in tree size-class distribution and population density over time. These plots are updated each year according to simulation results.

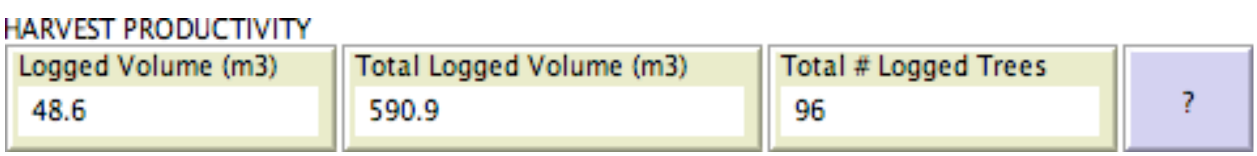


The **Diameter Distribution** plot shows the initial size-class distribution in **black**. This distribution is static. The current year size-class distribution is shown in **red**. This distribution updates each year according to simulation results. The diameter size classes are defined by 10-cm intervals and only trees ≥ 20 cm diameter are plotted. The vertical **gray** line divides commercial and non-commercial trees as determined by the minimum diameter cutting limit.

The **Tree Density** plot shows the density of trees over time (trees / 100 ha). The **black** line tracks the density of all trees ≥ 20 cm diameter. The **red** line tracks the density of commercial-sized trees. The vertical **gray** lines indicate the harvest years, that is, 1, 31, 61, and 91 years in the example shown.

8.3 Harvest Productivity Monitors

HARVEST PRODUCTIVITY monitors report the volume of trees logged in the most recent harvest as well as the number and volume of trees logged in all previous harvests. Monitors are updated after each logging event.



Logged Volume reports the volume (m^3) of trees logged in the most recent harvest.
Total Logged Volume reports the volume (m^3) of trees logged in all previous harvests.
Total # Logged Trees reports the number of trees logged in all previous harvests.

9 USER DATA UPLOAD

You can simulate population growth and harvest outcomes of a mahogany population at your own site using the **DATA UPLOAD** portion of the model interface. At minimum you will need diameter data for the trees within your site.

If you have both spatial distribution (mapping) and tree diameter data, you can upload the data from a spreadsheet or, if available, from a GIS shapefile. Refer below to ***Spatial Diameter Data: User Spreadsheet*** and ***Spatial Diameter Data: User Shapefile*** (**sections 9.1 & 9.2**), respectively, for instructions.

If you only have diameter data, you can upload the data from a spreadsheet, but you will need to know or estimate the dimensions or approximate area of your site. Refer to ***Non-Spatial Diameter Data: User Spreadsheet*** (**section 9.3**) below.

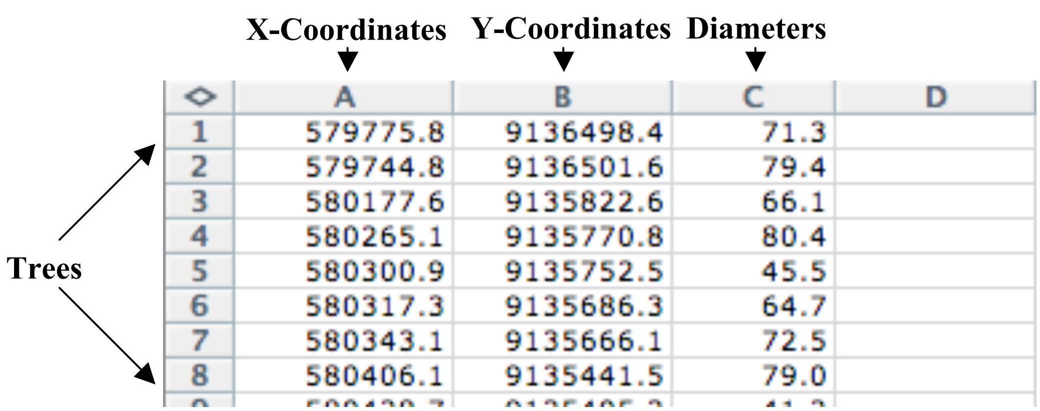
9.1 Spatial Diameter Data: User Spreadsheet

This section describes the procedures necessary to upload diameter data with spatial location information from a user spreadsheet. The spatial diameter data must be formatted according to the instructions below for the model to accept the user data.

Step 1. Data Structure and Format

The first step is to structure your data so the computer can read the information into the model. Create an Excel (.xls)-type spreadsheet to organize the data into three columns: X-coordinates, Y-coordinates, and tree diameters. The columns *must* be listed in this order for your data to be read into the model.

Column A should contain the X-coordinates (longitude) of each tree. *Column B* should contain the Y-coordinates (latitude) of each tree. *Column C* should contain the diameter in centimeters of each tree. DO NOT GIVE THE COLUMNS HEADERS. The head of your file should look like the example file shown below.



	A	B	C	D
1	579775.8	9136498.4	71.3	
2	579744.8	9136501.6	79.4	
3	580177.6	9135822.6	66.1	
4	580265.1	9135770.8	80.4	
5	580300.9	9135752.5	45.5	
6	580317.3	9135686.3	64.7	
7	580343.1	9135666.1	72.5	
8	580406.1	9135441.5	79.0	

The XY coordinates (longitude/latitude) *must* be measured in either meters or decimal degrees. In the example above, coordinates are given in UTM (Universal Transverse Mercator) geographic coordinate units taken from a standard GPS unit. Alternatively, coordinates could be given in user-assigned meter units derived from a field-based inventory.

Coordinates *cannot* be given in degrees, minutes, and seconds. Coordinates measured in this format can be converted here: http://www.fcc.gov/mb/audio/bickel/DDDMMSS-decimal.html.

Diameters *must* be measured in centimeters (cm). Tree diameter measurements should be taken at 1.3 m above the forest floor or at least 30 cm above the reach of the tallest buttress.

Step 2. Save As Text File

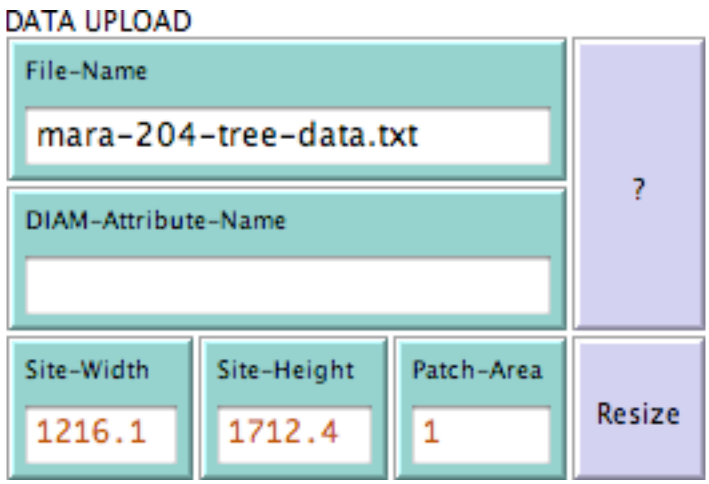
The model software cannot read data from Excel (.xls) files so the data must be saved as a text (.txt) file. In Excel or a similar spreadsheet program, choose *File* > *Save As* and select *Text (tab delimited)* from the *Save As* options. Include the *.txt* extension in the file name. The head of the new text file should look like this, WITHOUT COLUMN HEADERS:

	X-Coordinates	**Y-Coordinates**	**Diameters**
	579775.8	9136498.4	71.3
	579744.8	9136501.6	79.4
	580177.6	9135822.6	66.1
	580265.1	9135770.8	80.4
Trees	580300.9	9135752.5	45.5
	580317.3	9135686.3	64.7
	580343.1	9135666.1	72.5
	580406.1	9135441.5	79
	580428.7	9135405.3	41.2

Place the new text file in the *Model* > *User* folder. Remember the name of the new text file.

Step 3. NetLogo File Parameters

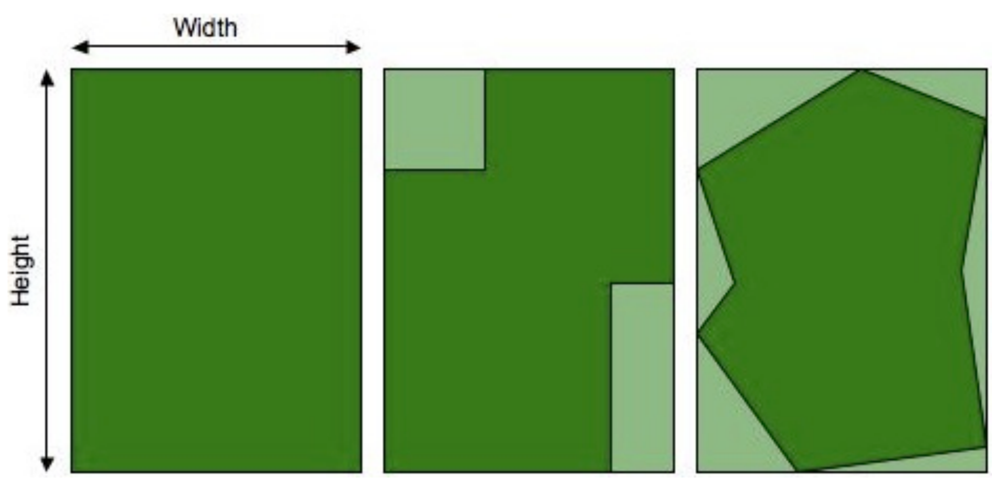
The final steps towards uploading your data into the model are completed in the **DATA UPLOAD** portion of the model interface. These parameters specify the name of the user data file, the dimensions of the user field site, and the resolution of the resulting landscape.



Type the name of the text file from Step 2 containing spatial and diameter data (located in the *User* folder) into the **File-Name** input box. Be sure to include the '.txt' file extension when typing the name.

Leave the **DIAM-Attribute-Name** input blank. This input is only necessary for data uploaded from a user shapefile (**section 9.2**). Input here will interfere with the present upload.

Type the width (X, in meters) of your site into the **Site-Width** input box and the height (Y, in meters) of your site into the **Site-Height** input box. If your site is not rectangular, estimate the width and height of the smallest bounding rectangle (examples shown below). Again, the width and height of your site must be in meters (m).



Type the value 1.00 into the **Patch-Area** input box. **Patch-Area** determines the size of landscape patches in pixels and therefore determines the size of the landscape. A **Patch-Area** of 1.00 is purposefully small and should draw a landscape contained by the available space on the model interface.

Step 4. Resize Site Drawing

After **File-Name**, **Site-Width**, **Site-Height**, and **Patch-Area** have been specified, press the **Setup** button under **MODEL SETTINGS** to draw your site on the model interface. If the site dimensions are incorrect, ensure that the file is formatted correctly (columns: X-coordinate, Y-coordinate, diameter). If you receive an error message, refer to ***Error Messages & Trouble Shooting*** (**section 9.4**) below.

The site should be drawn using a **Patch-Area** of 1.00 pixel but a larger or smaller **Patch-Area** may be preferred depending on the dimensions of your site. If the site is drawn too small for the available space, increase the **Patch-Area** by entering 2.00 and press the **Resize** button. If the site is drawn too large for the available space, decrease the **Patch-Area** by entering 0.50 and press the **Resize** button. Continue to make adjustments by increasing or decreasing the **Patch-Area** until you are satisfied with the size of your site projected onto the model interface.

Step 5. Trouble Shooting

If you require quick assistance, press the **?** button for a summary of the **DATA UPLOAD** features or refer to this manual. See ***Error Messages & Trouble Shooting*** (**section 9.4**) below for a discussion of error messages you may encounter when uploading your data into the model.

9.2 Spatial Diameter Data: User Shapefile

This section describes the procedures necessary to upload your data from a GIS shapefile. A shapefile is a file type produced by GIS software to store location and attribute data. This user data upload feature will not support any other geospatial file format.

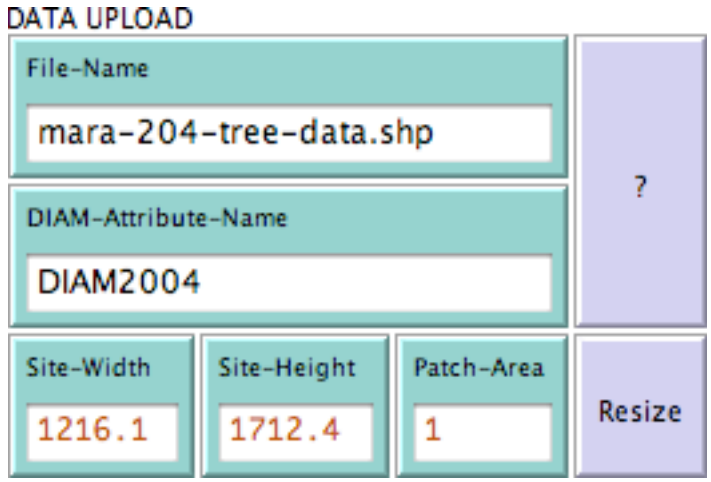
Step 1. Place Shapefile in User Folder

Place the shapefile containing spatial diameter data of your tree population in the *Model* > *User* folder. Place the dbf file (.dbf) associated with the shapefile here as well (the .prj, .sbn, .sbx, .shx, and .xml files are not necessary). Remember the name of the overarching shapefile (.shp).

Step 2. NetLogo File Parameters

Parameters in the **DATA UPLOAD** portion of the model interface shown on the next page specify the name of the user data file, the name of the diameter attribute, the dimensions of the field site, and the resolution of the landscape.

Type the name of the shapefile from Step 1 containing spatial and diameter data (located in the *User* folder) in the **File-Name** input box. Include the '.shp' file extension when typing the name. Type the name of the attribute (data column header) in the shapefile containing the diameter data in the **DIAM-Attribute-Name** input box. The diameters listed in the shapefile *must* be measured in centimeters (cm). Tree diameter measurements should be taken at 1.3 m above the forest floor or at least 30 cm above the reach of the tallest buttress.



Type the width (X, in meters) of your site into the **Site-Width** input box and the height (Y, in meters) of your site into the **Site-Height** input box. If your site is not rectangular, estimate the width and height of the smallest bounding rectangle (see examples, p. 20). Again, the width and height of your site must be in meters (m).

Type the value 1.00 into the **Patch-Area** input box. **Patch-Area** determines the size of landscape patches in pixels and therefore determines the size of the landscape. A **Patch-Area** of 1.00 is purposefully small and should draw a landscape contained by the available space on the model interface.

Step 3. Resize Site Drawing

After **File-Name**, **DIAM-Attribute-Name, Site-Width**, **Site-Height**, and **Patch-Area** have been specified, press the **Setup** button under **MODEL SETTINGS** to draw your site on the model interface. The site should be drawn using a **Patch-Area** of 1.00 pixel but a larger or smaller **Patch-Area** may be preferred depending on the dimensions of your site.

If the site is drawn too small for the available space, increase the **Patch-Area** by entering 2.00 and press the **Resize** button. If the site is drawn too large for the available space, decrease the **Patch-Area** by entering 0.50 and press the **Resize** button. Continue to make adjustments by increasing or decreasing the **Patch-Area** until you are satisfied with the size of your site on the model interface.

Step 4. Trouble Shooting

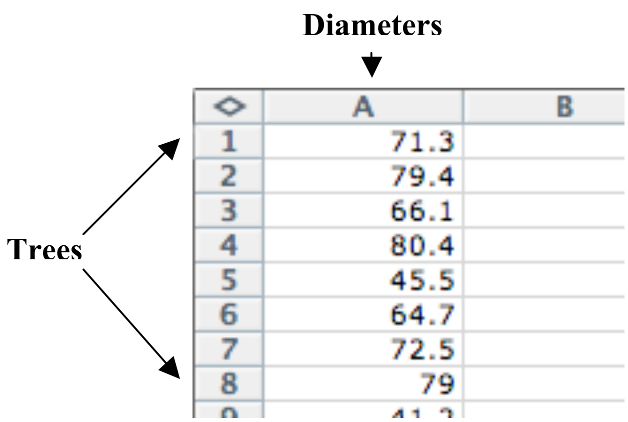
If you require quick assistance, press the **?** button for a summary of the **DATA UPLOAD** features or refer to this manual. See ***Error Messages & Trouble Shooting*** (**section 9.4**) below for a discussion of error messages you may encounter when uploading your data into the model.

9.3 Non-Spatial Diameter Data: User Spreadsheet

This section describes the procedures necessary to upload diameter data without spatial location information into the model interface. Although spatial diameter data is not required for this data upload feature, you must know or estimate the physical dimensions or area (ha) of your field site.

Step 1. Data Structure and Format

The first step is to structure your data so the computer can read the information into the model. Create a spreadsheet to organize the data into a single column: tree diameter (cm). DO NOT GIVE THE COLUMN A HEADER. The head of your file should look like this:



Diameters *must* be measured in centimeters (cm). Tree diameter measurements should be taken at 1.3 m above the forest floor or at least 30 cm above the reach of the tallest buttress.

Step 2. Save As CSV File

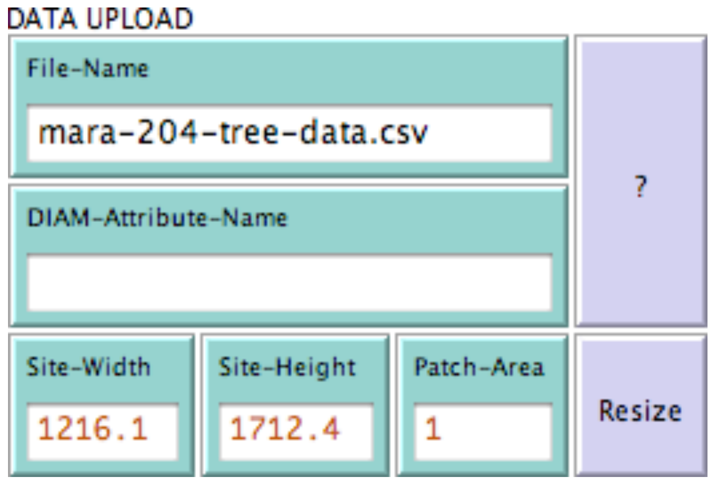
The model software cannot read data from Excel (.xls) or similar files; the data must be saved as a comma separated value (.csv) file. Choose *File* > *Save As* and select *CSV (comma delimited)* from the *Save As* options. INCLUDE THE '.CSV' EXTENSION IN THE FILE NAME.

Place the new .csv file in the *Model* > *User* folder. Remember the name of the .csv file.

Step 3. NetLogo File Parameters

The final steps towards uploading your data into the model are completed in the **DATA UPLOAD** portion of the model interface. These parameters specify the name of the user data file, the dimensions of the user field site, and the resolution of the resulting landscape.

Type the name of the .csv file from Step 2 containing diameter data (located in the *User* folder) into the **File-Name** input box. Be sure to include the '.csv' file extension when typing the name.



Leave the **DIAM-Attribute-Name** input blank. This input is only necessary for data uploaded from a user shapefile (**section 9.2**). Input here will interfere with the present upload.

Type the width (X, in meters) of your site into the **Site-Width** input box and the height (Y, in meters) of your site into the **Site-Height** input box. If your site is not rectangular, estimate the width and height of the smallest bounding rectangle (see examples, p. 20). Again, the width and height of your site must be in meters (m).

Type the value 1.00 into the **Patch-Area** input box. **Patch-Area** determines the size of landscape patches in pixels and therefore determines the size of the landscape. A **Patch-Area** of 1.00 is purposefully small and should draw a landscape contained by the available space on the model interface.

Step 4. Resize Site Drawing

After **File-Name**, **Site-Width**, **Site-Height**, and **Patch-Area** have been specified, press the **Setup** button under **MODEL SETTINGS** to draw your site on the model interface. The site should be drawn using a **Patch-Area** of 1.00 pixel but a larger or smaller **Patch-Area** may be preferred depending on the dimensions of your site.

If the site is drawn too small for the available space, increase the **Patch-Area** by entering 2.00 and press the **Resize** button. If the site is drawn too large for the available space, decrease the **Patch-Area** by entering 0.50 and press the **Resize** button. Continue to make adjustments by increasing or decreasing the **Patch-Area** until you are satisfied with the size of your site on the model interface.

Step 5. Trouble Shooting

If you require quick assistance, press the **?** button for a summary of the **DATA UPLOAD** features or refer to this manual. See ***Error Messages & Trouble Shooting*** (**section 9.4**) below for a discussion of error messages you may encounter when uploading your data into the model.

9.4 Error Messages & Trouble Shooting

If an error occurs while uploading your data, the model will stop the uploading process and present a message explaining the cause of the error. The following is a list of potential error messages and possible solutions.

A 'Population' must be selected. You selected the blank population option. Please select an actual population to simulate.

An 'Example Population' must be selected. You selected the **Example Population** heading. Please select an actual example population to simulate.

A 'User Population' must be selected. You selected the **User Population** heading. Please select an actual user population to simulate.

A 'File-Name' must be specified. You selected a **User Population** but did not specify a user data file. Please provide the name of the user data file or choose an example population.

'File-Name' must be a .txt file. You selected the **User Population (xyd)** option, which requires a user text file, but the file specified in **File-Name** does not have a .txt extension. Please ensure the file is a text file and has the text file extension (.txt).

'File-Name' must be a .shp file. You selected the **User Population (shp)** option, which requires a user shapefile, but the file specified in **File-Name** does not have a .shp extension. Please ensure the file is a shapefile and has the shapefile extension (.shp).

A 'DIAM-Attribute-Name' must be specified. You selected the **User Population (shp)** option, which requires a **DIAM-Attribute-Name**, but the **DIAM-Attribute-Name** field is empty. Please provide the name of the shapefile diameter attribute in this field.

'File-Name' must be a .csv file. You selected the **User Population (csv)** option, which requires a user csv file, but the file specified in **File-Name** does not have a .csv extension. Please ensure the file is a csv file and has the csv file extension (.csv).

'Site-Width' must be a positive non-zero number. You provided a non-zero (negative or zero) site width. Please provide a positive site width measured in meters (m).

'Site-Height' must be a positive non-zero number. You provided a non-zero (negative or zero) site height. Please provide a positive site height measured in meters (m).

'Patch-Area' must be a positive non-zero number. You provided a non-zero (negative or zero) patch area. Please provide a positive patch area measured in meters (m).

The site cannot be set up. Please review the file formatting / placement guidelines. You most likely received this error because the data file is formatted incorrectly or is not located in the *Model* > *User* folder. The data file should be placed in the *User* folder and should not have any headers, commas, spaces, or other symbols. Review this manual to ensure proper formatting.

9.5 User Data Upload Examples

There are example user files in the *Model > User* folder to help illustrate the user data upload process. The folder contains the files necessary to set up the **SE Pará (204ha)** population using each of the three user data upload methodologies.

The files and inputs required for each methodology are listed below. If you have any questions about formatting, look to these files as templates. If you have questions about the inputs, look to the information below and the **DATA UPLOAD** figures presented above (**sections 9.1, 9.2 & 9.3**).

Data Upload Type	File-Name	DIAM-Attribute-Name	Site-Width	Site-Height	Patch-Area
Spatial: TXT file	mara-204-tree-data.txt		1216.1	1712.4	1.0
Spatial: SHP file	mara-204-tree-data.shp*	DIAM2004	1216.1	1712.4	1.0
Non-Spatial: CSV file	mara-204-tree-data.csv		1216.1	1712.4	1.0

*The mara-204-tree-data.dbf file in the *Model > User* folder is associated with this shapefile and is necessary for data upload using this method.

10 EXPORT SIMULATION RESULTS

The monitors, plots, and landscape features provide a means for observing simulation results in real time, but these results are not stored in memory or elegantly summarized for the user. Simulation end results can be permanently stored and easily reviewed by pressing the **Export Results** button. The resulting file summarizes a given simulation by showing the model settings, harvest parameters, and initial population, final population, and harvest statistics.

Simulation results must be saved as a text (.txt) file. These files can be named and placed anywhere on your computer. It may be useful to name your file based on the simulated parameters. For example, *Marajoara-60cm-20rr-5md-30yr-1* indicates the population simulated, while *cm*, *rr*, *md*, and *yr* indicate the simulated minimum diameter cutting limit, retention rate, minimum density, and cutting cycle, respectively, and *1* indicates the simulation number.

Results text files can be opened with *Notepad* on Windows and *TextEdit* on Mac OS X. If you are missing either of these programs (they come pre-installed on your computer), free alternatives are available online. For Windows users, *Another Notepad* is a simple and free text editor: http://www.pc-shareware.com/anotepad.htm. For Mac users, *Plain Text Editor* is also a simple and free text editor: http://www.macupdate.com/app/mac/8724/plain-text-editor.

SIMULATION RESULTS, the head of the **Results** file, summarizes the model settings used in the completed simulation. This section lists: (1) the name of the field site (the data file name, if running a user population); (2) the area of the field site in hectares; (3) whether logging was turned on or off; and (4) the number of harvest cycles, the simulation time limit in years, and the actual time run in years.

The second section of the **Results** file reminds the user that additional simulations are necessary to validate the results of a single simulation. This can be achieved by repeating the same single-run simulation or by running a BehaviorSpace experiment as described in **section 11**.

The lines following these reminders define *Total Abundance/Density* and *Commercial Abundance/Density* as referred to in the **Results** file statistics. In all cases, *Total Abundance/Density* refers to trees ≥ 20 cm diameter. *Commercial Abundance/Density* refers to trees ≥ the minimum diameter cutting limit designated on the model interface.

The next section, **LOGGING PARAMETERS**, only appears if logging was turned on during the simulation and reports the logging parameter values used during the simulation. If the logging parameters are changed mid-simulation, only the end parameter values will be displayed.

YEAR 0 STATISTICS and **YEAR XXX STATISTICS** report the total density, commercial density, and commercial volume of the population in the initial and final years of the simulation. The year value in the **YEAR XXX STATISTICS** heading will be the final year of simulation, that is, a simulation lasting 100 years will read **YEAR 100 STATISTICS**.

The **HARVEST STATISTICS** section is only displayed if logging is turned on during the simulation. This section summarizes the number of harvests, number of trees logged, and volume of trees logged during the simulation runtime. The section also summarizes the results of each harvest by displaying the year and productivity of successive harvest events.

The **PRE/POST HARVEST ABUNDANCE & VOLUME** section summarizes the number and volume of commercial trees before/after each harvest if logging is turned on during simulations.

Finally, the **SIZE DISTRIBUTION (YEAR XXX)** section summarizes the size distribution of trees ≥ 20 cm diameter in the final year of simulation. The largest tree is always contained within the second largest size class, that is, the final size class will always contain 0 trees. The number of size classes changes based on the size distribution of trees in the final year but the size class increment is always 10 cm diameter.

11 SIMULATION EXPERIMENTS: BehaviorSpace

The NetLogo BehaviorSpace tool allows users to easily run repeat simulations of the Big-Leaf Mahogany Growth & Yield Model using either constant or systematically varied harvest parameter settings. The BehaviorSpace tool thus enables users to examine the outcomes of multiple harvest regimes with statistical confidence (repeat simulations) and methodological ease (automated process). Results from these simulations are then tabulated into a spreadsheet for analysis.

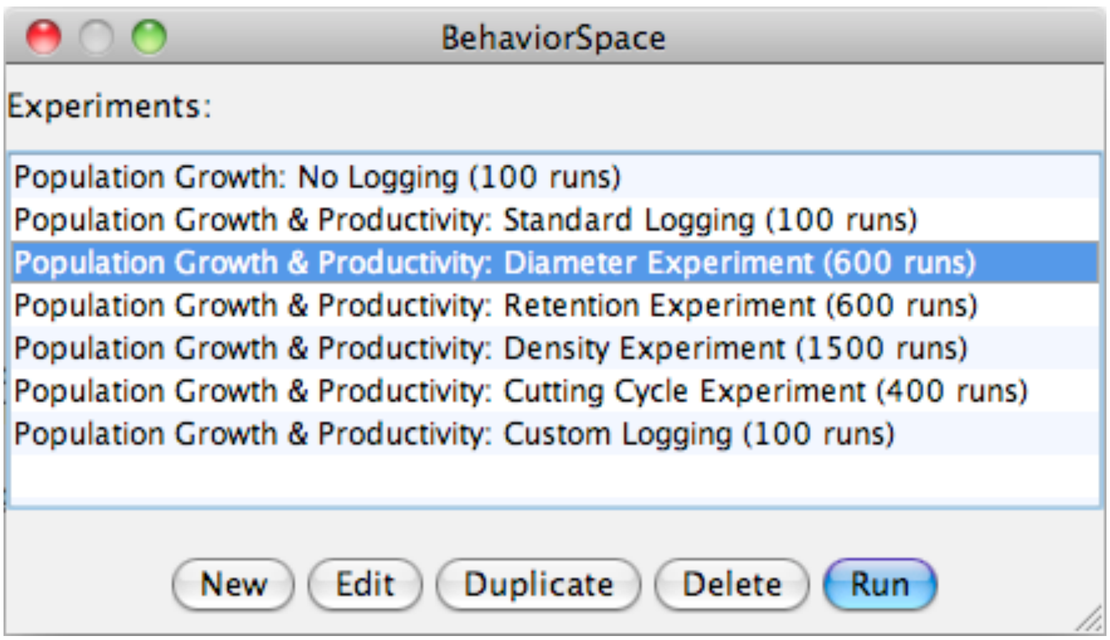
The following section explains how to run, modify, and analyze the seven built-in BehaviorSpace experiments.

Step 1. Define Model Parameters

BehaviorSpace experiments will systematically vary the harvest parameters but you must define the other model settings before running an experiment. Define **Populations**, **Logging**, and **Time** on the model interface according to the directions above (**section 6.2**). If you intend to simulate one or more harvest regimes, be sure that the **Logging** switch is turned on.

Step 2. Open BehaviorSpace

Open the BehaviorSpace tool by selecting **Tools > BehaviorSpace** in the NetLogo menu. The **BehaviorSpace** window will open in the center of your screen:



Seven built-in experiments are listed in this window. Resize the window to view the full experiment names by grabbing the triangle in the bottom-right corner. The function of each experiment is summarized below. The buttons in the **BehaviorSpace** window behave as follows:

New	creates a new BehaviorSpace experiment
Edit	opens the selected BehaviorSpace experiment for editing
Duplicate	duplicates the selected BehaviorSpace experiment
Delete	deletes the selected BehaviorSpace experiment
Run	runs the selected BehaviorSpace experiment

Before running an experiment, you should select the **Edit** option and familiarize yourself with the experiment's settings. The modification of these settings and the creation of new experiments are discussed more below (**section 12.2**).

Step 3. Choose a BehaviorSpace Experiment

Choose a baseline BehaviorSpace experiment to match your experimental goals:

The **Population Growth: No Logging** experiment simulates the initial population without logging in order to examine the natural projection of the population.

The **Population Growth & Productivity: Standard Logging** experiment simulates the initial population under current (default) harvest standards in order to examine population recovery after logging following these legal guidelines.

The four **Population Growth & Productivity: Harvest Parameter** experiments examine the effect of each harvest parameter on population growth and harvest productivity by varying a single harvest parameter and keeping the other parameters constant.

The final **Population Growth & Productivity: Custom Logging** experiment provides a place for the user to define a single custom harvest regime to simulate the recovery and productivity of the initial population under these guidelines.

Step 4. Examine & Modify a BehaviorSpace Experiment

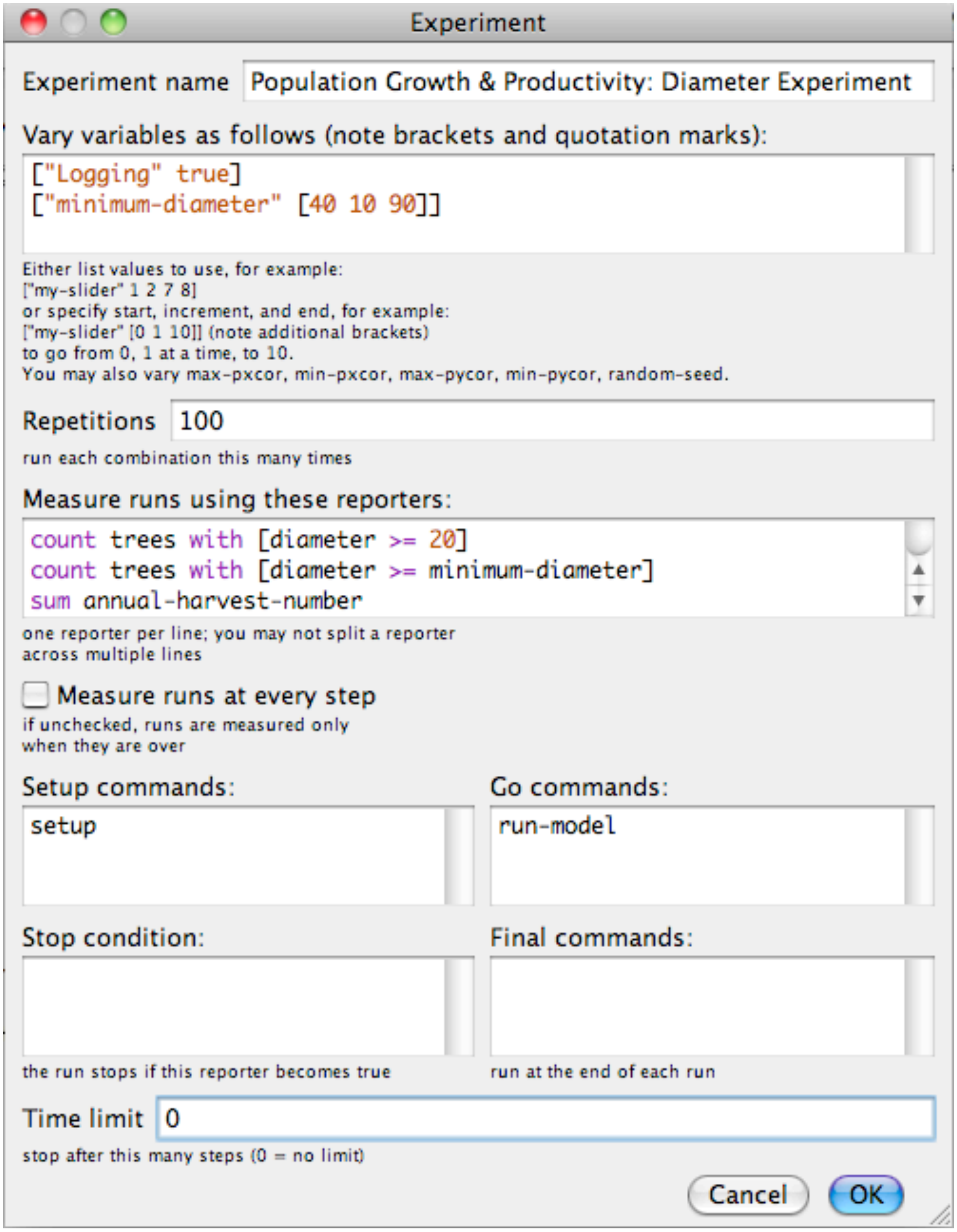
Select the chosen baseline experiment in the **BehaviorSpace** window by pressing the name of the experiment. The name should now be highlighted in blue. Press **Edit** to edit the details of the experiment. The **Experiment** window, shown on the next page, will open in the center of your screen.

Resize the window as needed by grabbing the triangle in the bottom-right corner. The window displayed on the next page describes the **Population Growth & Productivity: Diameter Experiment**, as listed in the **Experiment name** field at the top of the window.

Experiment Variables

The second field lists the **variables** to be examined during the BehaviorSpace simulation. In this experiment, logging is turned permanently on (*["logging" true]*) and the **minimum-diameter** is varied from 40 cm to 90 cm by increments of 10 cm (i.e., 40, 50, 60, 70, 80, 90 cm). All other harvest parameters and model settings will remain constant based on the current interface settings.

The **Vary variables** section has a similar structure in each experiment. **Population Growth: No Logging** is the only experiment with logging turned off because it is designed to monitor populations under natural conditions. **Population Growth & Productivity: Standard Logging**, unlike the other experiments, permanently sets the four harvest parameters because it is designed to monitor populations under current legal management practices for mahogany in Brazil.



The other four **Population Growth & Productivity** experiments (**Diameter**, **Retention**, **Density**, **Cutting Cycle**) vary each harvest parameter according to the syntax described above: [*"harvest-parameter"* [*start increment end*]]. To examine a different range or resolution of parameter values, change the *start*, *increment*, and *end* values according to preference.

Alternatively, values to be tested can be listed using the following syntax: [*"harvest-parameter" value value value ...*]. For example, [*"minimum-diameter" 50 55 60 75 80*] would simulate the non-incremental minimum diameters of 50, 55, 60, 75, and 80 cm. MAKE SURE YOU USE THE BRACKETS EXACTLY AS SPECIFIED.

The **Repetitions** field specifies the number of simulations performed for each harvest parameter value. The **Population Growth & Productivity: Diameter Experiment** simulates six minimum diameter values (40, 50, 60, 70, 80 and 90 cm), each 100 times, for a total of 600 simulations. Type a new number into the **Repetitions** field to increase or decrease the simulation sample size.

Experiment Reporters

The **Measure runs using these reporters** field designates the reporters, or measurements, used to evaluate the simulated population. The reporters for the **Diameter Experiment** are repeated in all other experiments (except **Population Growth: No Logging** which does not require harvest reporters) as measures of population growth and harvest productivity:

count trees	total tree abundance
count trees with [diameter >= small-diam]	abundance of trees ≥ 20 cm diameter
count trees with [diameter >= minimum-diameter]	abundance of commercial-sized trees
sum annual-harvest-number	summed number of logged trees
sum annual-harvest-volume	summed volume of logged trees
annual-harvest-number	number of trees logged in each harvest
annual-harvest-volume	volume of trees logged in each harvest
pre-post-cut-number	number of commercial trees before/after each harvest
pre-post-cut-volume	volume of commercial trees before/after each harvest

If you would like to remove a reporter from this list, simply delete it from the box. If you would like to add or modify a reporter, refer to the sections below (**sections 12.1 & 12.2**). Note: a method for reporting harvest number/volume statistics in individual columns is detailed in **section 12.2**.

The reporters will be measured every year (time step) if the **Measure runs at every step** option is selected. This would generate an unnecessary amount of data so the default setting leaves this option unchecked. If you would like to track *every* year of *every* simulation, select this option.

Experiment Run Settings

The **Setup commands** and **Go commands** fields correspond to the commands in the model procedure responsible for setting and running the model. DO NOT CHANGE THESE FIELDS.

The **Stop condition** and **Time limit** fields are left purposefully empty because both stop conditions and time limits are already built into the model. It would be redundant to specify them again here. DO NOT ENTER ANY VALUES OR COMMANDS IN THESE FIELDS.

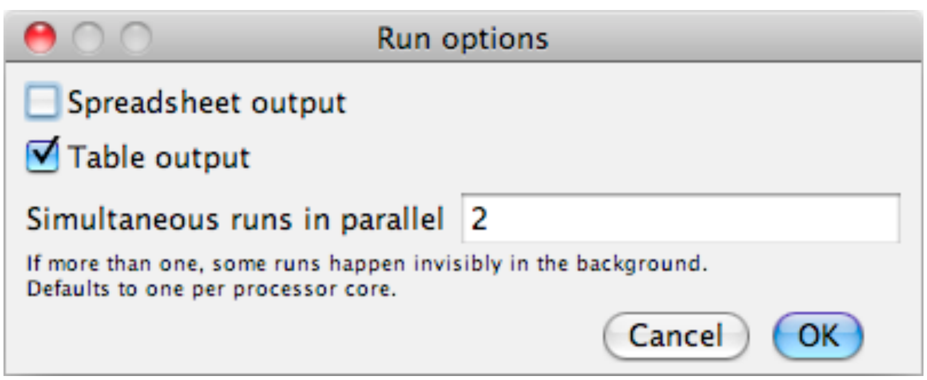
The **Final commands** field can be used to export the model landscape, plots, and world at the end of each model run. The *export-view* command exports the model landscape to an external image file. The *export-plot* and *export-all-plots* commands export either a specific plot or all plots to an external *.csv* file. The *export-world* command exports the values of all variables, both built-in and user-defined, including all observer, turtle, and patch variables and the plot contents. The commands for exporting each feature are as follows:

export-view (word "Results/" "View" behaviorspace-run-number ".jpg")
export-plot "Tree Density" (word "Results/" "Density" behaviorspace-run-number ".csv")
export-all-plots (word "Results/" "All Plots" behaviorspace-run-number ".csv")
export-world (word "Results/" "World" behaviorspace-run-number ".csv")

The exported files are all written to the *Model* > *Results* folder. Each file type is saved with a common identifier (i.e., 'view', 'plots', 'world') but is numbered according to its place in the BehaviorSpace experiment to prevent file overwriting. The *view* image can be saved with any image extension (*.jpg*, *.png*, *.bmp*, *.tif*, etc) but the plots and world files must be saved with the *.csv* extension.

Step 5. Run BehaviorSpace Experiment

Run the chosen experiment by selecting the experiment in the **BehaviorSpace** window and pressing the **Run** button. The **Run Options** window, shown below, will open in the center of your screen.

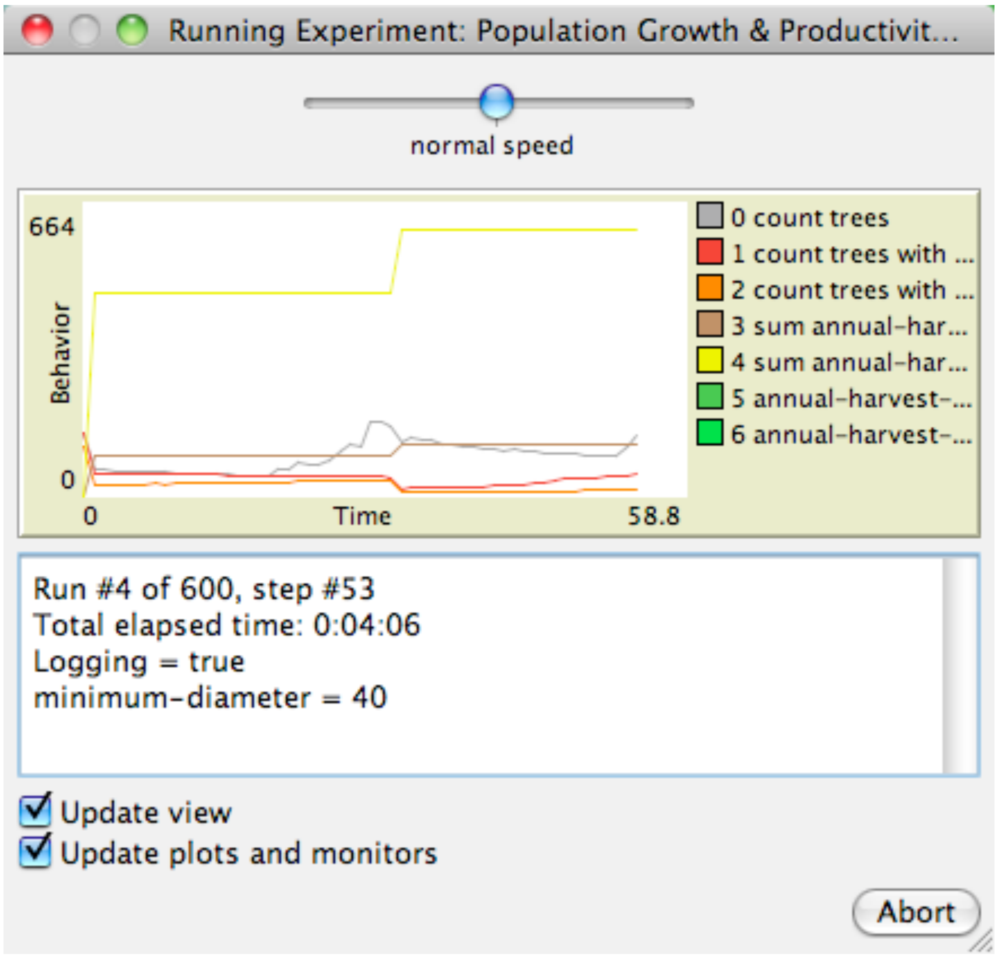


Check the **Table output** option and leave the **Spreadsheet output** option unchecked. Enter ***2*** into the **Simultaneous runs in parallel** field. The **Table output** option creates a more analysis-friendly output and the **Simultaneous runs in parallel** option = 2 maximizes run efficiency.

Press **OK** and save the output file anywhere on your computer. The output file must be saved as a .csv or .xls file. INCLUDE THE .CSV OR .XLS FILE EXTENSION IN THE FILE NAME.

Step 6. Determine Run Settings

After saving the output file, the **Running Experiment** window will open in the center of your screen. This window graphs the population metrics measured during the experiment and tracks the progress of the experiment by reporting the number of completed steps and elapsed time.



The graph will only be shown when measuring every time step; therefore, you will only see this graph if you change the default experiment settings. The graph displays the measure of each population metric over time, where the **Behavior** axis describes each metric. The metrics are color-coded according to the legend on the right.

The output window below the graph tracks the experiment progress. The window reports the number of completed *runs* and the number of completed *steps*, where each *step* represents a year. The total elapsed time is also reported. The experiments take some time to run, so please be patient.

The pace of the experiment can be accelerated by sliding the blue circle to the right, from **normal speed** to **faster speed**. Turning off the visuals will also reduce processing time: uncheck **Update view** and **Update plots and monitors** to further accelerate the experiment run time.

Pressing **Abort** will end the BehaviorSpace experiment. It is not possible to resume an aborted experiment. To continue a BehaviorSpace experiment after pressing **Abort**, you will need to start again from the beginning.

Step 7. Format Data Output

The **Running Experiment** window will close when the experiment is completed, returning the **BehaviorSpace** window to the center of the screen. Close the window and browse to the experiment results file. The head of the experiment results file should look like this:

◇	A	B	C	D
1	BehaviorSpace results (NetLogo 4.1.3)			
2	Growth & Yield Model 2.0.nlogo			
3	Population Growth: No Logging			
4	01/02/2012 10:21:17:259 -0500			
5	min-pxcor	max-pxcor	min-pycor	max-pycor
6	-63	63	-88	88

This section of the file records basic information about the simulation experiment including: (1) the version of NetLogo run; (2) the name of the model; (3) the name of the experiment; (4) the date and time the experiment was run; and (5) the dimensions of the field site. (Numbers in the above list correspond to the row number in the experiment results file.)

The field site dimensions are reported in terms of NetLogo patches but can be converted to meters by multiplying each value by 10 meters. The length of the X-axis of the site is the sum of minimum (*min-pxcor*) and maximum (*max-pxcor*) X-coordinates. The length of the Y-axis of the site is the sum of minimum (*min-pycor*) and maximum (*max-pycor*) Y-coordinates.

Additionally, we recommend inserting a few lines under the header to record additional information about the simulation experiment. For recordkeeping, it would be useful to record the field site name, area, and dimensions, initial tree abundance and volume, and harvest years.

The rows below the header contain the data from the simulation experiment. The headings can be rewritten for increased clarity based on the following recommendations or on user preference:

[run number]	Run
Logging	Logging (on/off)
minimum-diameter	Minimum Diameter (cm)
retention-rate	Retention Rate (%)
minimum-density	Minimum Density (# / 100 ha)
cutting-cycle	Cutting Cycle (yr)
[step]	Time (yr)
count trees	# Trees
count trees with [diameter >= 20]	# Trees (≥ 20 cm diameter)
count trees with [diameter >= minimum-diameter]	# Commercial Trees
sum annual-harvest-number	# Logged Trees
sum annual-harvest-volume	Logged Tree Volume (m^3)

annual-harvest-number	Harvest Number List (# / yr)
annual-harvest-volume	Harvest Volume List (m^3 / yr)
pre-post-cut-number	Pre/Post Harvest Commercial Abundance
pre-post-cut-volume	Pre/Post Harvest Commercial Volume (m^3)

If you would like to query the model for additional information, please refer to ***Command Line*** and ***Modifying BehaviorSpace Experiments*** below (**sections 12.1 & 12.2**).

Step 8. Analyze Simulation Data

Before analyzing the data, you may be interested in adding a few data columns, such as total density, commercial density, and harvest year statistics. The abundance (count) values can be converted to density values using the following formula:

$$Density = (Abundance / Site\ Area) * 100$$

where site area is measured in hectares (ha) and density is measured in trees per 100 hectares.

The harvest number and volume lists can be broken into individual years using the *Text to Columns* feature available in most spreadsheet programs. First, highlight the columns containing harvest lists and use the *Find and Replace* feature to remove the brackets ('[') from the cells. Then, use the *Text to Columns* feature, with data delimited by spaces, to convert the text data to column data. This will better facilitate the examination of harvest productivity across time.

The post-processing of the harvest value lists can be avoided by using the directions in ***Harvest List Reporters*** of ***Modifying BehaviorSpace Experiments*** (**section 12.2**) to report the harvest list values in individual columns as opposed to a single column list. Label these new columns accordingly.

The analysis of the experiment data should be performed according to your familiarity with statistics. A thorough review of statistical analysis is beyond the scope of this User Manual; however, simple statistics, such as average and standard deviation, should suffice most of the time. For example, a comparison of the average final commercial density to the initial commercial density is a simple but powerful statistical method.

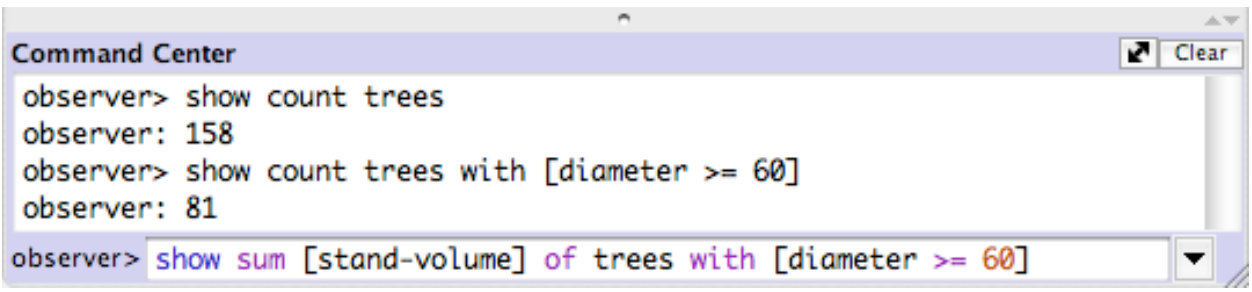
Similarly, calculating the average logged volume from each harvest year provides a simple but powerful summary of harvest productivity over time under different harvest regimes. A standard deviation of these averages would provide an estimate of confidence. The BehaviorSpace experiments provide a large sample size and these simple statistics can convey much information about population growth and harvest productivity.

12 ADVANCED USERS & NETLOGO RESOURCES

12.1 Command Line Code

The following section provides an introduction to using the **Command Center** to query the landscape for information not displayed in the population monitors or plots or harvest monitors.

Commands are entered in the command line window, the small window labeled **observer>**, shown below. The results of the commands are printed in the larger output window labeled **Command Center**.



Copy and paste any of the italicized commands listed below into the command line window. Press *Return/Enter* to run the command. ALWAYS LEAVE THE COMMAND LINE IN OBSERVER MODE. DO NOT SUBMIT COMMANDS IN TURTLES, PATCHES, OR LINKS MODES.

You can access previous commands using the history popup menu, the small downward pointing triangle to the right of the command line window. Press the triangle to see a menu of previously entered commands. Alternatively, you can access previous commands with the *UP* and *DOWN* keys on the computer keyboard, as long as the cursor is in the command line window.

Pressing the **Clear** button in the upper-right corner of the **Command Center** window will erase the contents of the output window. Additionally, the **Command Center** can be resized by grabbing and moving the gray bar at the top of the **Command Center** window.

The following is a list of commands that may be useful to your analysis. For sections with ***bold italicized*** commands (i.e., ***grow-trees***, ***kill-trees***, ***log-trees***, etc.), you must enter the ***bold italicized*** command before entering the other commands. The commands can be modified using the statements at the bottom of the summary to more powerfully query the model results.

POPULATION STATISTICS

total tree abundance	*show count trees*
commercial tree abundance	*show count trees with [diameter >= 60]*
first-year-seedling abundance	*show count trees with [seedling? = true]*

total tree volume (m^3)	*show sum [stand-volume] of trees*
maximum tree basal area (cm^2)	*show max [basal-area] of trees*
median small tree diameter (cm)	*show median [diameter] of trees with [diameter <= 20]*
median tree age (yr)	*show median [age] of trees with [age < 1000]*
initial population abundance	*show y0-tree-density * site-area / 100*
initial population density	*show y0-tree-density*
initial commercial abundance	*show y0-comm-density * site-area / 100*
initial commercial density	*show y0-comm-density*
commercial density (trees / 100ha)	*show count trees with [diameter >= 60] / site-area * 100*

Note that if you are asking questions about tree ages, be sure to omit trees older than 1000 years, as shown above (see 'median tree age (yr)'). These are the initial trees whose ages are unknown ('1000 years' is simply a marker).

FIELD SITE STATISTICS

field site area (m^2)	*show site-area * 10000*
field site area (ha)	*show site-area*
field site area (km^2)	*show site-area / 100*
field site width (m)	*show world-width * 10*
field site width (km)	*show world-width * 10 / 1000*
field site height (m)	*show world-height * 10*

GROWTH STATISTICS: *grow-trees*

specific tree growth rate (cm/yr)	*show [growth-rate] of tree 17*
median tree growth rate (cm/yr)	*show median [growth-rate] of trees*
fastest growing tree diameter (cm)	*show [diameter] of trees with-max [growth-rate]*
fastest growing tree (tree #)	*show [who] of trees with-max [growth-rate]*
smallest basal area tree (tree #)	*show [who] of trees with-min [basal-area]*
largest trees: 50th percentile (tree #s)	*show [who] of trees with [diameter > median [diameter] of trees]*

HARVEST STATISTICS: *log-trees*

last harvest: number of logged trees	*show length cur-logged-volume*
last harvest: total logged volume (m^3)	*show sum cur-logged-volume*
last harvest: largest logged tree volume (m^3)	*show max cur-logged-volume*
all harvests: number of logged trees	*show length tot-logged-volume*
all harvests: total logged volume (m^3)	*show sum tot-logged-volume*
all harvests: largest logged tree volume (m^3)	*show max tot-logged-volume*

number of trees logged in harvest number x	*show item (x - 1) annual-harvest-number*
volume of trees logged in harvest number x	*show item (x - 1) annual-harvest-volume*

number of commercial trees before / after harvests:

before	*show n-values (length pre-post-cut-number / 2) [item (? * 2) pre-post-cut-number]*
after	*show n-values (length pre-post-cut-number / 2) [item (? * 2 + 1) pre-post-cut-number]*

commercial volume before harvest x	*show item ((x - 1) * 2) pre-post-cut-volume*
commercial volume after harvest x	*show item ((x - 1) * 2 + 1) pre-post-cut-volume*
commercial density before / after harvests	*show map [? / site-area * 100] pre-post-cut-number*

the volume of every tree logged during the simulation	*tot-logged-volume*
the volume of every tree logged during the most recent harvest	*cur-logged-volume*
the total number of trees logged during each harvest	*annual-harvest-number*
the total volume of trees logged during each harvest	*annual-harvest-volume*
the total number of commercial trees before / after each harvest	*pre-post-cut-number*
the total volume of commercial trees before / after each harvest	*pre-post-cut-volume*

MORTALITY STATISTICS: *kill-trees*

specific tree mortality probability	*show [mort-prob] of tree 17*
median tree mortality probability	*show median [mort-prob] of trees*
live tree mortality probabilities	*show [mort-prob] of trees with [alive? = true]*

dead tree abundance	*show count trees with [alive? = false]*
large dead tree abundance	*show count trees with [alive? = false and diameter >= 60]*
dead tree diameter list (cm)	*show [diameter] of trees with [alive? = false]*

DISTURBANCE STATISTICS: *disturb-trees*

landscape disturbance (%)	*show count patches with [disturbance? = true] / count patches*
landscape sweetspot (%)	*show count patches with [sweetspot? = true] / count patches*

landscape disturbance (ha)	*show count patches with [disturbance? = true] * 100 / 10000*
landscape sweetspot (ha)	*show count patches with [sweetspot? = true] * 100 / 10000*

REPRODUCTION STATISTICS: *reproduce-trees*

reproductive tree abundance	*show count trees with [reproduce? = true]*
mean reproductive tree diameter	*show mean [diameter] of trees with [reproduce? = true]*

max large tree fruit probability	show *max [fruit-prob] of trees with [diameter <= 30]*
median fruit production	*show median [num-fruit] of trees with [reproduce? = true]*

potential seed production	*show floor (sum [num-fruit] of trees * seeds-per-fruit)*
actual seed production	*show sum [seedlings] of trees*

DISTURBANCE / SEEDLING DATASETS

median disturbance area (m^2)	*show median disturbance-data*
disturbance dataset sample size	*show length disturbance-data*
view disturbance dataset	*show disturbance-data*
mean first-year-seedling diameter	*show mean seed-diam-data*
max first-year-seedling growth rate	*show max seed-growth-data*

list of disturbance area sizes (m^2) observed in the field	*disturbance-data*
list of first-year-seedling diameters (cm) observed in the field	*seed-diam-data*
list of first-year-seedling growth rates (cm/yr) observed in the field	*seed-growth-data*

Note that distributions for disturbance, seedling diameter, and seedling growth rate can be viewed in the *Model > Data* folder. The disturbance size distribution is called *gap-data.csv*. The seedling diameter and growth distributions are called *seed-diam-data.csv* and *seed-growth-data.csv*, respectively.

EXPORT DATA

export landscape image (.jpg)	*export-view user-new-file*
export interface image (.jpg)	*export-interface user-new-file*
export output text (.txt)	*export-output user-new-file*
export single plot values (.csv)	*export-plot "tree density" user-new-file*
export all plot values (.csv)	*export-all-plots user-new-file*
export all variables (.csv)	*export-world user-new-file*

Note that you can name and place exported files anywhere on your computer. Include file extensions as listed in parenthesis above following each export method.

AVAILABLE STATEMENTS

math statements	*<, >, =, !=, <=, >=*
logic statements	*true, false*
statistical statements	*max, min, mean, median, modes, with-min, with-max*
patch variables	*disturbance?, sweetspot?*
tree variables	*who, age, alive?, seedling?, fall-gap? reproduce?, diameter, basal-diameter, basal area, stand-volume, sawn-volume, growth-rate, mort-prob, fruit-prob, num-fruit, seedlings*

These statements can be substituted for similar statement types in the *italicized* commands provided above. For example, any statistical statement (*max, min, mean,* etc.) can replace a statistical statement in the provided commands. Likewise, any tree variable (*age, alive?, diameter, mort-prob, seedlings,* etc.) can replace a tree variable in the provided commands.

12.2 Modifying BehaviorSpace Experiments

SIMULATION EXPERIMENTS: BehaviorSpace (**section 11**) provides a thorough review of the NetLogo BehaviorSpace feature. If you are interested in personalizing the built-in experiments further, or in creating your own experiments entirely, please review the section below.

Varying Multiple Parameters

Pre-defined BehaviorSpace experiments are designed to test either a single harvest regime or to test the sensitivity of population growth & yield to a single harvest parameter. It is also possible to examine multiple harvest regimes within a single simulation experiment. This can be achieved by varying more than one harvest parameter in the BehaviorSpace variable settings.

For example, rather than only varying **minimum-diameter**, both **minimum-diameter** and **retention-rate** could be varied using the following code:

["minimum-diameter" [40 10 80]]
["retention-rate" [10 5 30]]

The BehaviorSpace experiment would simulate each combination of **minimum-diameter** and **retention-rate** for the specified number of repetitions. In other words, each minimum diameter cutting limit, beginning with 40 cm and ending with 80 cm at 10-cm increments, would be simulated with each retention rate, beginning with 10% and ending with 30% at 5% increments.

This design can be implemented with all four harvest parameters to simulate the outcomes of multiple harvest regimes. Although it generates many runs, and therefore requires a lot of processing time, it collects the results in a single spreadsheet for quick analysis.

Adding New Reporters

The built-in experiments can also be personalized by adding new reporters or stop conditions to the experiment settings. New reporters can be added from those listed in ***Command Line Code*** (**section 12.1**) although reporters requiring ***bold italicized*** commands will not generate meaningful data since BehaviorSpace reporters are measured at the end of each run.

Copy and paste the **Command Line** reporters (exclude *show* from the reporter) into the BehaviorSpace reporter settings. For example, rather than pasting *show median [diameter] of trees with [diameter <= 20]*, only paste *median [diameter] of trees with [diameter <= 20]*. These reporters will provide additional information when running experiments.

Harvest List Reporters

The *annual-harvest-number* and *annual-harvest-volume* reporters print a list of harvest values in two columns as *[item*$_{h1}$ *item* $_{h2}$ *item* $_{h3}$ *item* $_{h4}$ *...]* where each *item*$_{hx}$ represents the harvest value for harvest number *x*. If you prefer that each item receive its own column, you must replace the *annual-harvest-volume* reporter with the following reporters:

item 0 annual-harvest-volume	volume of logged trees in harvest 1
item 1 annual-harvest-volume	volume of logged trees in harvest 2
item 2 annual-harvest-volume	volume of logged trees in harvest 3
item (1 – X) annual-harvest-volume	volume of logged trees in harvest X

The *item* code numbers items in a list from zero onwards so *item 0* is harvest 1, *item 1* is harvest 2, *item 3* is harvest 4, etc. You must enter an *item* reporter for each expected harvest. You can determine the expected number of harvests using the following formula:

floor (time / cutting-cycle) + 1

where the 'floor' of a number of harvests is the largest integer less than or equal to the number.

Pre/Post Harvest List Reporters

The *pre-post-cut-number* and *pre-post-cut-volume* reporters print a list of harvest values in two columns as $[item_{pre\text{-}h1}\ item_{post\text{-}h1}\ item_{pre\text{-}h2}\ item_{post\text{-}h2}\ ...]$ where $item_{pre\text{-}x}$ and $item_{post\text{-}x}$ represent a population statistic before and after harvest number *x*, respectively. If you prefer that each item receive its own column, you must replace the *pre-post-cut-number* reporter with the following reporters:

item 0 pre-post-cut-number	number of commercial trees before harvest 1
item 1 pre-post-cut-number	number of commercial trees after harvest 1
item 2 pre-post-cut-number	number of commercial trees before harvest 2
*item ((X - 1) * 2) pre-post-cut-number*	number of commercial trees before harvest X
*item ((X - 1) * 2 + 1) pre-post-cut-number*	number of commercial trees after harvest X

The *item* code numbers items in a list from zero onwards so *item 0* is the first value, *item 1* is the second value, *item 2* is the third value, etc. You must enter two *item* reporters for each expected harvest. You can determine the expected number of harvests using the following formula:

floor (time / cutting-cycle) + 1

where the 'floor' of a number of harvests is the largest integer less than or equal to the number.

Adding Stop Conditions

If you are interested in including stop conditions different from the defaults, which stop simulations after the time limit or when all trees die or are harvested, you can enter new conditions in the **Stop condition** prompt. The model stops when conditions become true. For example, if you want to halt simulations after the first harvest, you would enter: *length annual-harvest-number > 0*. Alternatively, if you want to halt simulations when commercial abundance falls below a certain threshold, you would enter: *count trees with [diameter >= minimum-*

diameter] <= 10. In this example, simulations would stop when commercial abundance falls below 10 trees.

More information on BehaviorSpace experiments can be found on the NetLogo website or in the NetLogo User Manual. Please see ***NetLogo Resources*** (**section 12.4**) below.

12.3 Model Procedure Code

This section provides insight into understanding and modifying the underlying model code.

A fully annotated version of the model code is available in ***APPENDIX E: MODEL CODE*** (**page 68**) and in the **Procedures** tab of the NetLogo interface. A close review of the code will help you better understand how the model works.

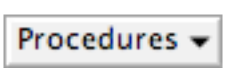
Procedure Summary

At the top of the model code you will find basic information about the model: title, authors, funders, landscape dimensions, etc. Throughout the code, gray text on the right side preceded by repeated semi-colons (;;) represents comments provided to help interested users understand how the code operates. This text is not read by the computer.

The first section of functional model code, ***EXTENSIONS, BREEDS, AND VARIABLES***, identifies code extensions and variables used throughout the model. Code extensions activate code types not included in the default language as well as variables used throughout the model to modify trees and the landscape. Breeds identify "trees" as the agents, or individuals, simulated by the model. Global variables are constant values used to make these modifications; these are the only variables we suggest that you modify, as explained below.

MODEL SETUP, the second section of code, sets up the model by checking for errors, setting variable values, drawing the landscape, setting the plots and monitors, and establishing the initial population on the landscape. These steps happen in discrete sections of code known as procedures, bounded by the keywords *to* and *end*. Each step is explained thoroughly in the comments.

The third section of code, ***RUN MODEL***, successively grows, kills, disturbs, and reproduces trees on the landscape. This section also resets the trees and landscape in preaparation for the next year of simulation. These steps are also contained within procedures and each procedure is extensively commented in the model code. The fourth and final section, ***EXPORT RESULTS***, contains the code for exporting the results of a single model simulation to a text file.



In the **Procedures** tab of the NetLogo interface, use the **Procedures** menu to view a list of model procedures and zoom to a specific procedure.

Procedures are color-coded according to the following scheme: keywords are **green**; constants are **orange**; comments are gray; built-in NetLogo commands are **blue**; primitive reporters are **purple**; and everything else is **black**.

Modifying Global Variables

It is possible to modify the growth & yield model using alternative data to calculate alternative regressions, but explaining this process is beyond the scope of this User Manual. If you intend to modify model functions, we recommend that you modify only *global variables* (model constants). Global variables are set in the first section of code and are briefly summarized below.

Variable	Value	Definition
prop-land-dist	0.026	proportion of the landscape disturbed each year
seed-shadow-area	0.91	area (ha) of a mahogany tree's seed shadow
max-num-fruit	750	maximum number of fruit per tree
seeds-per-fruit	42.4	average number of viable seeds per fruit
establishment-rate	0.085	proportion of seeds surviving to become first-year seedlings

To change the value of any of these constants, simply replace the old value with a new one. Remember to rename the new model when saving to avoid overwriting the original model. OVERWRITING THE ORIGINAL MODEL WILL FORCE YOU TO REINSTALL THE MODEL.

The ability to redefine global variables is useful for personalizing the model constants to your field site. For example, if you think your site experiences more disturbance, increase the proportion of landscape disturbance (*prop-land-dist*) value. Similarly, if you think the trees in your site have a smaller maximum fruit output (*max-num-fruit*) or produce fewer viable seeds per fruit (*seeds-per-fruit*), you can reduce these values.

12.4 NetLogo Resources

NetLogo is a multi-agent programmable modeling environment developed by Uri Wilensky at the Center for Connected Learning and Computer-Based Modeling (Wilensky 1999). If you are interested in learning more about the software, please visit the NetLogo website:
http://ccl.northwestern.edu/netlogo/index.shtml

The website offers resources for learning NetLogo including a User Manual, online dictionary, example models, and publications. The NetLogo Users Group, an online community of NetLogo users, is also available for help and advice: http://groups.yahoo.com/group/netlogo-users/

The NetLogo software comes with a **Models Library**, available in **Files > Models Library** in the NetLogo menu. These models can be used as examples or templates for learning the NetLogo language, modifying the growth & yield model, or creating new NetLogo models.

NetLogo 4.1.3, the version used to run the Big-Leaf Mahogany Growth & Yield Model, can be downloaded here: http://ccl.northwestern.edu/netlogo/4.1.3/. The most recent version of the software can be downloaded here: http://ccl.northwestern.edu/netlogo/download.shtml

13 LIMITATIONS & CONSIDERATIONS

The Big-Leaf Mahogany Growth & Yield Model functions are derived from demographic data collected annually from 1995–2010 for nearly 600 mahogany trees and many thousands of seedlings, saplings and pole-sized trees at multiple field sites in southeast Pará and Acre. This comprehensive dataset allows for robust predictions of mahogany population growth & yield outcomes over reasonable time periods. Even so, it is important to acknowledge model limitations that constrain the accuracy and precision of projected outcomes.

First, due to the scarcity of natural regeneration in gap environments, simulated seedling/sapling mortality and growth rates in large gaps are based on data from experimental outplantings across light gradients in large clearings initiated at Marajoara in 1995. These data present *optimistic* estimates of juvenile performance due to manual removal of competing vines and secondary vegetation during the experiments' initial three years.

Second, population outcomes are highly sensitive to disturbance, and the model's disturbance function is derived from data collected during a single year at Marajoara. Because disturbance regimes vary widely across time and space, this data only partially represents the temporal and spatial extent of gap-forming disturbance events necessary for mahogany regeneration and recruitment to adult size.

Finally, the model does not formally incorporate density-dependent population regulation, which may allow *overestimation* of population growth & yield. *Steniscadia poliophaea*, a nocturnal specialist moth, preys more regularly and intensely upon mahogany seedlings in close proximity to large fruiting trees or groups of clumped adults. The population-level influence of this density-dependent seedling predator could be strong if population growth is sensitive to observed reductions in seedling survival and growth. See Norghauer *et al*. references (**section 16**) for more information on this topic. As well, impacts on population growth of the mahogany shootborer, *Hypsipyla grandella*, cannot be directly accounted for in the model due to lack of data addressing this issue. Density-dependent seedling mortality has been shown to reduce population growth rates in other neotropical trees.

14 FUTURE MODIFICATIONS

We are interested in using the recently published *R Extension for NetLogo* (Thiele & Grimm, in press: http://netlogo-r-ext.berlios.de/) to increase the robustness of the model regressions, the potential for in-model data analysis, and the functionality of the Export Results command.

We also plan to make the model compatible with NetLogo 5.0 when it is officially released (Wilensky 1999: http://ccl.northwestern.edu/netlogo/5.0/docs/). The new version of NetLogo will provide a richer reference section in the *Info* tab, support for international characters throughout the model application, and improved performance and processing time.

The online version of the model will be updated as the computer version of the model becomes more compatible with the web server and applet export services.

Future versions of the model may also be improved according to user feedback and recommendations. Please take the user survey listed on our website: http://www.swietking.org

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17 CONTACT US

If you have questions about the model, please email Chris Free: cfree@swietking.org. If you are unable to email, questions can be directed to:

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More information on our research can be found on our website (http://www.swietking.org) or in the publications listed above.

APPENDIX A: DATA SOURCES

This research program's principal study site, Marajoara, is a forest industry-owned management area in southeast Pará, Brazil (7°50' S, 50°16' W). The site was selectively logged for mahogany between 1992–1994. Model demographic parameters are derived from a sample mahogany population consisting of 358 surviving trees > 10 cm diameter in an area of 2050 ha. These trees were censused annually for survival, stem diameter growth, and fruit production from 1997-2010. Other phases of mahogany's life cycle, including temporal and spatial patterns of seed dispersal, seed germination, and seedling establishment rates, were quantified in observational and experimental studies at Marajoara. Fruit production data are supplemented by observations of ~325 mahogany trees at three additional sites in southeast Pará and at the Acre/West Amazon site. Because few large (> 100 cm diameter) adult trees survived logging at Marajoara or were available for observation at the other study sites, fruit production data are supplemented with data from Gullison *et al.* (1996).

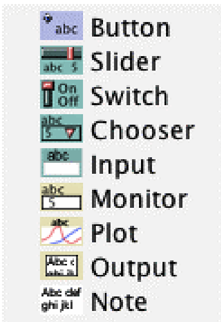
The example populations, discussed at greater length in **section 6.1**, were derived from: (1) a 100%-area inventory of mahogany trees ≥ 20 cm diameter in a 204-ha subplot of the Marajoara field site; (2) a randomly stratified transect survey of mahogany trees ≥ 20 cm diameter in 1035 ha at Marajoara (10% of the total area); and (3) a 100%-area inventory of mahogany trees ≥ 20 cm diameter in 685 ha at the Acre/West Amazon site. Due to selective logging prior to the study, mortality and growth rates may reflect a small post-logging increase.

Due to the scarcity of natural regeneration in gap environments, simulated seedling/sapling mortality and growth rates in large gaps are based on data from experimental outplantings across light gradients in large clearings initiated in 1995. These data present optimistic estimates of juvenile performance due to the manual removal of competing vines and secondary vegetation during the experiments' initial three years.

Canopy disturbances are simulated based on an observed size distribution of gap-forming canopy gaps during 1996–1997 at Marajoara.

APPENDIX B: MODEL DETAILS & DEFINITIONS

MODEL FEATURES



Button: A button executes instructions when pressed. **Setup**, **Defaults**, **Run 1 Year**, **Run X Years**, **Resize**, **All Definitions**, **Export Results**, **?**, etc., are all buttons.

Slider: A slider allows selection from a range of values. The model has sliders for **Time** and **LOGGING PARAMETERS**.

Switch: A switch allows a variable to be turned on/off. The **Logging** switch turns the logging function on/off before simulation.

Chooser: A chooser allows a user to choose among variable values. The **Populations** chooser allows the user to select between three example populations and three user-defined population options.

Input: An input box allows the user to type in a value for a variable. There are two types of inputs: number and text. The **Site-Width**, **Site-Height**, and **Patch-Area** input boxes accept number inputs. The **File-Name** and **DIAM-Attribute-Name** input boxes accept text inputs.

Monitor: A monitor displays the value of a built-in expression. The **Area**, **Population**, and **Harvest Productivity** monitors report the area of the field site, the density/volume of trees in the initial and current populations, and the number/volume of trees logged during harvests.

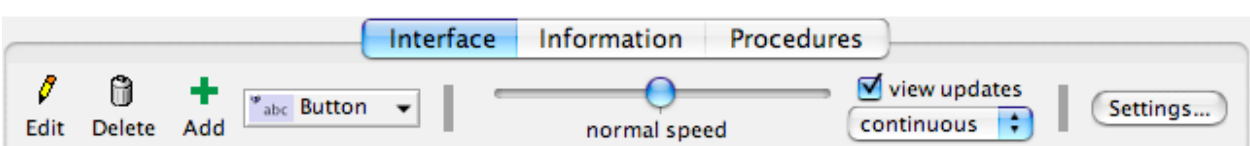
Plot: A plot provides a real-time graph of model results. The **Diameter Distribution** plot tracks the size distribution of the population and the **Tree Density** plot tracks tree density.

Output: An output provides a text window on the model interface. The **Definitions** output provides definitions of the interface features when the **?** (**Help**) buttons are pressed.

Note: A note provides text labels for each section of features. **MODEL SETTINGS**, **LOGGING PARAMETERS**, **YEAR 0 POPULATION**, etc., are all provided to organize and structure the interface.

INTERFACE DEFINITIONS (see schematic, page 3)

MODEL CONTROL BAR



The **Interface** tab displays model controls and simulations.
The **Information** tab displays basic information about the model.
The **Procedures** tab displays the workspace where the model code is stored and modified.

Edit: This button is only active when a feature is selected on the interface. Pressing the button allows the selected feature to be edited. Use it to modify the range/increment of a harvest parameter.

Delete: This button is only active when a feature is selected on the interface. Pressing the button will delete the selected feature. Do not use this button! All features are necessary to the model.

Add + Button: In combination, these add buttons, sliders, switches, choosers, inputs, monitors, plots, outputs, or notes to the interface. First press **Add** and then **Button** to choose a feature from the pop-up menu.

normal speed: This slider determines the speed of model runs. Slide the round knob left for slower, slide right for faster.

view updates: Determines whether landscape updates are shown. When checked, you can view **continuous** updates or **on ticks** updates (that is, at the end of each year). Unchecking **view updates** yields faster model runs.

Settings: Determines the size, shape, and resolution of the landscape, and sets the time unit.

MODEL CONTROLS

MODEL CONTROLS

Setup	establishes initial population on landscape
Defaults	resets harvest and other parameters to default conditions
Populations	lists selection of example and user-defined initial populations
Site Area	area of selected site in hectares (ha)
Logging	determines whether logging is on/off during the simulation(s)
Time	number of years the model will simulate
Run 1 Year	runs the model for one year
Run X Years	runs the model until time limit or all trees are harvested or die
?	help button returns definitions for a given model section

LOGGING PARAMETERS

Minimum-Diameter	minimum diameter of commercial trees (cm)
Retention-Rate	retention rate of commercial-sized trees (%)
Minimum-Density	minimum post-harvest density of commercial trees (trees / 100 ha)
Cutting-Cycle	number of years between harvests

YEAR 0 / CURRENT POPULATION

Total Density	density of trees ≥ 20 cm diameter in the field site (trees / 100 ha)
Commercial Density	density of commercial-sized trees in the field site (trees / 100 ha)
Commercial Volume	volume of timber in the commercial population (m^3)
Diameter Distribution	bar columns = 10-cm diam increments; gray line = commercial diam **black** = initial size distribution; **red** = current size distribution
Tree Density	vertical gray lines = harvest years **black** line = total tree density; **red** line = commercial tree density

Commercial-sized trees, or commercial trees, are trees whose diameters are larger than the minimum diameter cutting limit, or *minimum-diameter*. Note that in both **Diameter Distribution** and **Tree Density** plots, no trees < 20 cm diameter are shown.

HARVEST PRODUCTIVITY

Logged Volume	volume of trees logged in the most recent harvest (m^3)
Total Logged Volume	volume of trees logged in all previous harvests (m^3)
Total # Logged Trees	number of trees logged in all previous harvests

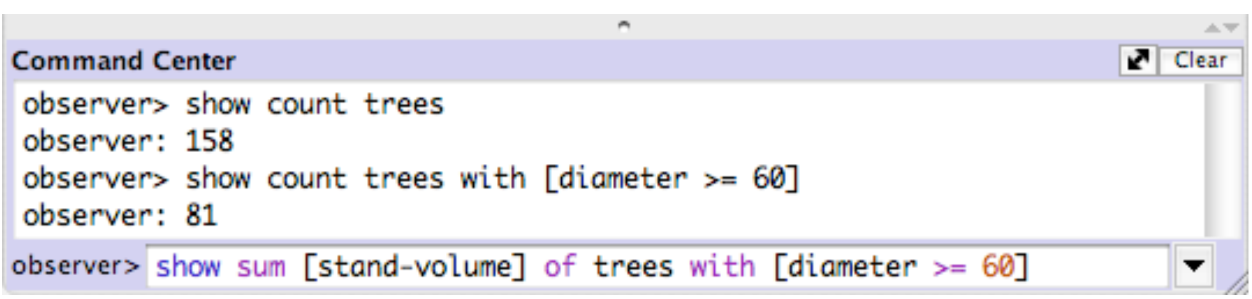
DATA UPLOAD

File-Name	name of user data file with diameter and or XY data
DIAM-Attribute-Name	name of the diameter attribute in the user shapefile
Site-Width	width (X) of the user field site (meters)
Site-Height	height (Y) of the user field site (meters)
Patch-Area	size of the patches on the landscape (pixels)
Resize	resizes the landscape based on the 'Patch-Area' listed

DEFINITIONS

All Definitions	displays the definition/function of all features on the interface
Export Results	exports simulation results to a user named and located file

COMMAND CENTER



The **Command Center** allows commands to be issued directly, without adding them to the model's procedures. This is useful for extracting more specific information about the population than default outputs provide.

observer>: This pop-up menu specifies the **Command Center** mode. It can be changed to turtles, patches, or links modes, but should be left in **observer** mode.

 Click on the **History** triangle to browse and select from previously typed commands.

 This button switches the **Command Center** window between vertical window and horizontal views. Other resizing options include: Drag the gray bar separating the window from the interface to a new position. Or, press the small gray arrows above the 'Clear' button to hide the window or make it very large.

Clear: Press this button to clear the contents of the **Command Center** window. To clear the **History** pop-up menu, choose 'Clear History' in the menu options.

APPENDIX C: MODEL FUNCTIONS

This section provides an in-depth review of how the model functions. ***APPENDIX E: MODEL CODE*** (**page 68**) provides a similar review alongside the actual model code. The fully annotated model code is also available in the **Procedures** tab of the NetLogo interface.

Initial Population

The model begins with an initial population selected by the user and represented on the NetLogo landscape. The landscape is contained within a box where each cell represents a 10 m x 10 m (100 m^2) patch on the landscape. Disturbances and seeds dispersed over a landscape edge are not returned on the other side. Because the model is spatial, the arrangement of trees on the landscape is significant in determining simulation outcomes.

At each time step (one year), the following demographic parameters are estimated for each tree based on regression equations derived from field census data: (1) diameter increment (cm yr^{-1}); (2) mortality probability; (3) probability of fruit production; and (4) number of fruit produced. The model simulates logging, growth, mortality, disturbance, and reproduction each year with these parameters until the time limit is exceeded or all trees are harvested or die.

Growth Function

The growth function incorporates growth autocorrelation, the tendency of fast-growing trees to remain fast growing, in order to account for past growth history. Diameter increment is estimated as a function of stem diameter using generalized least squares to incorporate an autoregressive error term, accounting for growth autocorrelation over the preceding ten years.

The trees begin the simulation with no growth history, so the residuals, *e1* (1 year previous), *e2* (2 years previous), *e3* (3 years previous), etc., are assigned a random value drawn from the distribution *N(0, 0.48)*. The present year residual, *e0*, is then calculated as follows:

$$e0 = (0.399 * e1) + (0.321 * e2) + (0.081 * e3) + (-0.046 * e4) + (0.130 * e5) + (-0.143 * e6) + (-0.029 * e7) + (0.266 * e8) + (0.190 * e9) + (0.311 * e10) + \sigma \quad (1)$$

where $\sigma \sim N(0, 0.48)$. The residuals are recalculated each time step because, as a year passes, the residual of the previous year becomes the residual of two years before. The residuals are therefore recalculated as *e10 = e9, e9 = e8, …, e2 = e1*, *e1 = e0*, and *e0* = the value of the above equation calculated with the new residual values. The growth rate, or diameter increment, of each tree is then calculated using the following equation:

$$growth\ rate\ (cm\ yr^{-1}) = 0.42 + (basal\text{-}diameter * 0.007) - (0.009 * max(0, basal\text{-}diameter - 40)) + e0 \quad (2)$$

where the *max(0, diameter – 40)* evaluates to zero when a tree is ≤ 40 cm diameter and evaluates to (*diameter – 40)* when a tree is > 40 cm diameter. The resulting diameter increment is added to the current diameter to calculate the new tree diameter. A diameter increment < 0 is reclassed as

0 given the impossibility of negative growth.

Logging Function

The logging function removes eligible trees from the population at the beginning of the simulation and during the subsequent harvest years, as determined by the cutting cycle parameter. The function removes the maximum number of trees larger than the minimum commercial size without violating either retention rate or post-harvest density requirements. Trees selected for logging are randomly stratified across the size distribution of eligible trees. Half of logged trees are allowed to disperse seeds prior to death and all logged trees create canopy gaps proportional to stem diameter based on equations in the ***Mortality Function*** section below (equations 5 & 6).

Mortality Function

The mortality function estimates the probability of mortality as a binary logistic regression of the current year stem diameter and diameter increment using the following equation:

$$\begin{aligned} \textit{log-odds(mortality)} = -0.083 - (4.177 * GR) + (3.705 * \max(0, GR - 0.4)) + \\ (2.57 * \max(0, GR - 1.5) - (0.575 * BD) + (0.554 * \max(0, BD - 5)) + \\ (0.027 * \max(0, BD - 25)) + (0.00077 * \max(0, BD - 85)) \end{aligned} \quad (3)$$

where *GR* is the current year diameter increment and *BD* is the basal diameter. The *log-odds* is subsequently used to calculate the probability of mortality using the logit transformation:

$$\textit{mortality probability} = (\exp \textit{log-odds}) / (1 + (\exp \textit{log-odds})) \quad (4)$$

where the fate of each tree is determined by comparing its probability of mortality to a random number between 0 and 1. If the randomly selected number is smaller than the probability of mortality, the tree is marked as dead.

Before its removal from the population, a dead tree is given a 50% chance of dying standing and a 50% chance of dying before reproducing. A tree dying after reproducing will fruit and disperse seeds before being removed from the population, whereas a tree dying before reproducing will be removed from the population without fruiting. A tree dying standing will be removed from the population without creating a treefall gap, whereas a tree resulting in a treefall gap will create a disturbance area according to the following equation:

$$\textit{disturbance area } (m^2) = -25.171 + (1.398 * \textit{diameter}) + (0.02 * \textit{diameter} \wedge 2) \quad (5)$$

where *diameter* is calculated from basal diameter using the following equation:

$$\textit{diameter (cm)} = (\textit{basal diameter} - 0.2842709) / 1.1003362 \quad (6)$$

The radius of the disturbance area is calculated using the equation for the area of a circle, $a = \pi r^2$. The zone of recruitment, that is, the area of the disturbance available for seedling recruitment, is estimated to be 10 m shorter in radius than the radius of the disturbance area. The resulting disturbance and zone of recruitment areas are constructed on the landscape using the tree as the center of each circular area.

Disturbance Function

The model disturbs the landscape as follows: (1) an initial batch of disturbances is added to the landscape; (2) additional disturbances are then added one at a time until a certain proportion of the landscape is disturbed; and (3) disturbances representing treefall gaps are added last. The model calculates the number of batch disturbances to add to the landscape based on the area of the field site and the size of the landscape disturbance proportion; larger field sites and larger landscape disturbance proportions receive more disturbances in batch. After placement of batch disturbances, the model adds disturbances one at a time until the proportion of landscape disturbance matches the specified proportion (default = 0.026). Treefall gaps are placed after the proportion is achieved in order to prevent them from counting towards the background disturbance rate. Disturbance sizes are drawn from a gamma distribution fit to an observed size distribution of gap-forming canopy disturbances (n = 87; shape: 0.6127; scale: 0.0056). All disturbances are circular and the radius of the zone of recruitment is 10 m less than the radius of the whole disturbance; therefore, a disturbance with a radius > 10 m is necessary for recruitment. The zones of recruitment represent the only viable areas for recruitment on the landscape as recruitment does not occur in the forest understory or on the outer edge of canopy disturbances.

Reproduction Function

Fruiting probability is estimated as a binary logistic regression of the current year stem diameter and diameter increment of trees marked as reproductive (all non-seedling trees and 50% of dead mahogany trees) using the following equation:

$$\text{log-odds(fruiting)} = -9.624 + (0.210 * \text{basal-diameter}) - (0.182 * \max(0, \text{basal-diameter} - 40)) + (3.201 * \text{growth-rate}) - (1.165 * \text{growth-rate} \wedge 2)) \quad (7)$$

which is subsequently used to calculate the fruiting probability using the logit transformation:

$$\text{fruiting probability} = (\exp \text{log-odds}) / (1 + (\exp \text{log-odds})) \quad (8)$$

If fruiting occurs, fruit production is estimated as a function of current year stem diameter and diameter increment in a generalized linear model with a gamma error term. The gamma distribution function is parameterized with the scale and shape factors, *alpha* (α) and *lambda* (λ). The α value is a constant 1.142 while the λ value is calculated as a function of the α value and the mean number of fruit. The mean number of fruit for a tree of any given diameter is calculated using the following equation:

$$\text{mean-fruit} = \exp(0.29583 + (0.02453 * \text{diameter}) + (0.00033 * \text{basal-diameter} \wedge 2) - (1.744 * 10 \wedge -6 * \text{basal-diameter} \wedge 3)) \quad (9)$$

These values are subsequently used in the calculation of λ, which, in conjunction with α, is used to parameterize the gamma distribution describing the distribution of fruit production values for a single tree. These two equations are as follows:

$$lambda = \alpha / mean\text{-}fruit \quad (10)$$

$$fruit\ production = gamma(\alpha, \lambda) \quad (11)$$

where fruit production by a given tree is capped at 750 to avoid unrealistically high values.

After fruit production is determined for reproductive trees, these trees disperse their seedlings within the surrounding seed shadow. The number of seedlings after one year is calculated as follows:

$$1\text{-}year\text{-}old\ seedlings = fruit_i * s_{fruit} * f_{surv} \quad (12)$$

where $fruit_i$ is the number of fruit produced by tree i, s_{fruit} is the mean number of seeds per fruit, and f_{surv} is the fraction of seeds that germinate and survive to become 1-year-old seedlings. s_{fruit} and f_{surv} are constant values of 42.4 and 0.085, respectively, based on observations at the Marajoara field site. One-year-old seedlings are dispersed evenly within the 0.91-ha circular seed shadow (53.8 m radius) of the parent tree. Because seedling recruitment is only possible within the interior portions of disturbance areas, only seedlings landing in the zone of recruitment (sweetspot) of a disturbance survive. All others die and are no longer tracked in the model.

Model Reset Function

The final function in the model procedure resets the trees and landscape before beginning the process again during the next time step (the next year). First, all dead trees and disturbances are removed from the landscape. Second, the tree variables associated with reproduction – fruiting probability, fruit production, and number of surviving seeds – are reset to default values to prevent the values of a reproductive year from carrying over into a non-reproductive year.

APPENDIX D: VERSION DIFFERENCES

The following document is a summary of the changes made to the Big-Leaf Mahogany Growth & Yield Model (Version 1.0) since it was first released in January 2011.

VARIABLE NAMES

The following variable names have been updated for increased clarity. The new names in **bold** provide a better summary of function and purpose than the old names (*italics*).

Global Variables

- **y0-tree-density** (*y0-tot-density*) – specifies tree density in initial year
- **prop-land-dist** (*prop-dist*) – specifies proportion landscape disturbance
- **disturbance-data** (*disturbance-dataset*) – contains gap size data
- **prob-die-no-repro** (*prob-die-no-seeds*) – specifies the probability of a tree dying before fruiting in the year of its death
- **establishment-rate** (*surv-prob*) – specifies seedling survival rate
- **seed-diam-data** (*seed-diam-list*) – contains seedling diameter data

Tree Variables

- **diameter** (*dbh*) – specifies stem diameter
- **basal-diameter** (*diameter*) – specifies stem basal diameter
- **stand-volume** (*volume*) – specifies standing volume
- **mort-prob** (*mort-rate*) – specifies probability of mortality
- **seedlings** (*surv-seeds*) – specifies number of seedlings

NEW VARIABLES

The following variables have been added to increase functionality of the model.

Global Variables

- **small-diam** – specifies minimum size of trees to plot/monitor
- **growth-sigma** – specifies standard deviation of growth residuals
- **num-batch-dist** – specifies how many batch disturbances to build
- **no-recruit-dist** – specifies non-recruitment distance in canopy gaps
- **large-dist?** – specifies whether large-scale disturbances occur
- **large-dist-prob** – specifies probability of large-scale disturbance
- **large-dist-area** – specifies area of large-scale disturbance
- **seed-shadow-area** – specifies the area of a tree's seed shadow; eliminates *seed-radius*
- **seed-growth-data** – new list contains seedling growth data
- **pre-post-cut-number** – new list contains live tree abundance pre- & post-harvest
- **pre-post-cut-volume** – new list contains live tree volume pre- & post-harvest
- **harvest-ticker (removed)** – removed because of new harvest method

Tree Variables

- **age** – specifies age of tree; ages of initial trees are unknown
- **fall-gap?** – specifies whether a tree creates a treefall gap
- **sawn-volume** – specifies sawn volume
- **e4-e10** – specifies growth residuals from 4 to 10 years previous

MODEL SETUP

Helper Functions: The new model has six 'helper functions' to perform calculations repeated throughout the model. These functions help protect against copy/paste errors and simplify the model code. The helper functions are summarized as follows:

Function Name	Function Purpose	Function Location
calc-e0	calculates e0 residual	setup-tree-values; update-residuals; disperse-seeds
calc-diam	calculates diameter	calculate-diameter; disperse-seeds
calc-basal-diam	calculates basal diameter	setup-tree-values
calc-basal-area	calculates basal area	setup-tree-values; calculate-diameter; disperse-seeds
calc-stand-volume	calculates stand volume	setup-tree-values; calculate-diameter; disperse-seeds
calc-sawn-volume	calculates sawn volume	setup-tree-values; calculate-diameter; disperse-seeds

Volume Equation: The old standing volume equation was replaced with a new equation derived from field studies in Guatemala (Kometter 2011).

Site Area: The site area is now specified for example populations and calculated for user populations in the *setup-world* procedure. The specification of example population site areas allows calculation of more accurate population densities.

World Shapefiles: The example populations are now constructed using shapefiles that define the extent of the population on the landscape (world). This prevents trees, rivers, and boundaries from being placed against the edge of the NetLogo world boundary.

User Shapefile Upload: The code for displaying user shapefiles was modified to fix a bug which halted the model when trees were placed on the world (landscape) edge. The new code expands the world envelope to contain the tree envelope and eliminate the bug.

PLOTTING

Plotting is now done through a setup/update procedure. This both prepares the current model for eventual upgrade to NetLogo 5.0 and reduces processing time. The new plotting setup function also sets the initial X- and Y-axis sizes to minimize auto-adjusting during model runs.

The *Tree Abundance* plot has been replaced by the *Tree Density* plot. The new plot shows the density of trees per 100 hectares over time using the symbology of the original abundance plot (all trees shown in black; commercial trees shown in red).

GROWTH FUNCTION

Growth Residuals: The growth function now incorporates 10 years of growth autocorrelation and therefore has ten years of growth residuals. In Year 0, the growth residuals of previous years are randomly drawn from a normal distribution. The present-year (*e0*) growth residual is calculated using a new equation derived from the incorporation of new data.

Growth Rate: The growth function uses a new equation for determining the annual growth increment. The equation was derived from the incorporation of new data.

LOGGING FUNCTION

Year 1 Logging: The logging of trees in Year 1 now occurs before the growth function (and all others); logging still occurs after the growth function in other harvest years.

Harvest Years: The logging function uses a new method for determining whether the present year is a harvest year, comparing the present year to the list of harvest years. This method is more elegant than the old *harvest-ticker* method.

Stratified Random Logging: The logging function now stratifies the logging of trees by diameter size class. This change reflects actual logging practices more accurately.

Minimum Density: The logging function now prevents the violation of the minimum density requirement. Previously, a bug often allowed an extra tree to be logged in violation of the minimum density parameter.

Pre/Post Harvest Statistics: The logging function now records the abundance and volume of commercial-sized trees alive before and after each harvest.

MORTALITY FUNCTION

Mortality Probability: The mortality function uses a new equation for determining the probability of mortality. The equation was derived from the incorporation of new data.

DISTURBANCE FUNCTION

Disturbance: The disturbance procedure no longer includes mahogany treefall gaps in the landscape disturbance rate of 2.6%. A *fall-gap?* tree variable was created to accommodate these changes.

Batch Disturbance: The disturbance function now places an initial batch of disturbances on the landscape before adding the disturbances necessary to achieve the specified landscape disturbance rate. This function greatly increases the speed of the model.

REPRODUCTION FUNCTION

Fruiting Probability: The reproduction function uses a new equation for determining the probability of fruiting. The equation was derived from the incorporation of new data.

Fruit Production: The reproduction function uses a new equation for determining fruit production. The equation was derived from the incorporation of new data.

Seed Dispersal: The reproduction function uses a new method for dispersing seeds; the new method uses the standard approach to uniform seedling dispersal. Although the new function might be slightly slower, it produces a truly random and uniform distribution.

Seedling Growth Rate: The seedling growth rates are now drawn from the seedling growth rate distribution; seedling growth rates were previously set to zero.

Seedling Growth Residuals: The *e10* growth residual is now calculated from seedling growth rate data. The *e9-e1* growth residuals are set to zero and the *e0* growth residual is calculated using a new equation, derived from the incorporation of new data.

EXPORT RESULTS

Export Results Function: The name of the export results function was changed from *export-data* to *export-results* for increased clarity and accuracy.

Pre-/Post-Harvest Statistics: The export function now displays the abundance and volume of commercial-sized trees alive before and after each harvest in the exported text file.

BEHAVIORSPACE

View, Plot & World Export: If exporting a view, plot, or world from a BehaviorSpace experiment, use the *behaviorspace-run-number* code in place of the *date-and-time* code when naming the output file. The old code does not work on Windows computers.

APPENDIX E: MODEL CODE

This section provides a fully annotated copy of the model code. This code is identical to the code in the **Procedures** tab of the NetLogo interface. The structure of the model code is summarized in ***Model Procedure Code*** (**section 12.3**) and reviewed briefly below.

The head of the model code provides basic information about the model: title, authors, funders, landscape dimensions, etc. The ***EXTENSIONS, BREEDS, AND VARIABLES*** section declares the code extensions and variables used throughout the model. The ***MODEL SETUP*** section sets up the model by checking for errors, setting variable values, drawing the landscape, setting the plots and monitors, and establishing the initial population on the landscape. The ***RUN MODEL*** section successively grows, logs, kills, disturbs, and reproduces trees on the landscape. This section also resets the trees and landscape in preaparation for the next year of simulation. The ***EXPORT RESULTS*** section contains the code for exporting the results of a single model simulation to a text file.

The procedures are color-coded according to the following scheme: keywords are **GREEN**; constants are **ORANGE**; comments are GRAY; built-in NetLogo commands are **BLUE**; primitive reporters are **PURPLE**; and everything else is **BLACK**.

```
;; Model Info
;; ================================================

;; Title: Big-Leaf Mahogany Growth & Yield Model (Version 2.0)
;; Authors: Christopher Free, R. Matthew Landis, James Grogan

;; Funding: International Institute of Tropical Forestry (USFS-IITF),
;; ITTO-CITES Program for Implementing CITES Listings of Tropical Timber Species

;; NetLogo Platform: NetLogo 4.1.3, http://ccl.northwestern.edu/netlogo/4.1/docs/

;; Model Info: A spatially explicit individual-based population growth and yield model of big-leaf mahogany (Swietenia macrophylla King).

;; POPULATIONS: AREA, SIZE, DENSITY
;; SE Pará (204ha): 158 trees, 77.5 trees / 100 ha
;; SE Pará (1035ha): 745 trees, 72.0 trees / 100 ha
;; Acre/West Amazon (685ha): 81 trees, 11.8 trees / 100 ha

;; LANDSCAPE INFO
;; Each patch is a 10m x 10m square. The world is contained within a box;
;; seeds dispersed off the landscape (world edges) are not tracked by the model.

;; LANDSCAPE DIMENSIONS: SE Pará (204ha)                                 ;; LANDSCAPE DIMENSIONS: SE Pará (1035ha)
;; World Area: 224.79 ha = 1270 m x 1770 m                               ;; World Area: 1175.85 ha = 3350 m x 3510 m
;; Patch Dimensions: 127 patches x 177 patches                           ;; Patch Dimensions = 335 patches x 351 patches
;; NetLogo Dimensions: 63 patches x 88 patches (1/2 above)               ;; NetLogo Dimensions = 162 patches x 175 patches (1/2 Above)
;; TRUE AREA: (63 x 2 + 1) * (88 x 2 + 1) * 100 / 10000 = 224.79 ha     ;; TRUE AREA = (162 x 2 + 1) * (175 x 2 + 1) * 100 / 10000 = 1175.85 ha

;; LANDSCAPE DIMENSIONS: Acre/Amazon (685ha)
;; World Area: 1093.95 ha = 4950 m x 2210 m
;; Patch Dimensions: 495 patches x 221 patches
;; NetLogo Dimensions: 246 patches x 110 patches (1/2 above)
;; TRUE AREA: (246 x 2 + 1) * (110 x 2 + 1) * 100 / 10000 = 1093.95 ha

;; EXTENSIONS, BREEDS, AND VARIABLES
;; ==========================================================================================

extensions [gis]                ;; This turns on the GIS code extension.

breed [trees tree]              ;; This specifies trees as the model agents.

globals [                       ;; MODEL CONSTANTS
  errors?                       ;; A Boolean indicating whether errors were detected during setup (true/false).
  site-area                     ;; The area (ha) of the selected field site (for both example and user populations).
  small-diam                    ;; The diameter (cm) of the smallest trees tracked during simulations.
  y0-tree-density               ;; The initial density (trees/100ha) of trees larger than the small-diam.
  y0-comm-density               ;; The initial density (trees/100ha) of trees larger than commercial-size.
  y0-comm-volume                ;; The initial standing volume (m3) of trees larger than commercial-size.
  growth-sigma                  ;; The standard deviation of the growth residual normal distribution.
  prop-land-dist                ;; The annual proportion of landscape disturbance.
  num-batch-dist                ;; The number of disturbances to place on the landscape at once (in batch).
  no-recruit-dist               ;; The distance (m) from a gap edge in which recruitment is impossible.
  disturbance-data              ;; The gap size (m2) distribution of the Marajoara field site.
  large-dist?                   ;; A Boolean indicating whether large-scale disturbances are implemented during simulations.
  large-dist-prob               ;; The probability of a large-scale disturbance occurring.
  large-dist-area               ;; The area (ha) of large-scale disturbances.
  prob-die-standing             ;; The probability of a tree dying standing in the year of its death.
  prob-die-no-repro             ;; The probability of a tree dying before fruiting in the year of its death.
  seed-shadow-area              ;; The area (ha) of a tree's seed shadow.
```

```
  max-num-fruit                 ;; The maximum number of fruit per tree.
  seeds-per-fruit               ;; The average number of seeds per fruit.
  establishment-rate            ;; The proportion of seeds surviving to become first-year seedlings.
  seed-diam-data                ;; The seedling diameter (cm) distribution.
  seed-growth-data              ;; The seedling growth rate (cm/yr) distribution.
  tot-logged-volume             ;; A list of the standing volumes (m3) of trees logged during all previous harvests.
  cur-logged-volume             ;; A list of the standing volumes (m3) of trees logged during the most recent harvest.
  annual-harvest-volume         ;; A list of the sum standing volumes (m3) of trees logged during each harvest.
  annual-harvest-number         ;; A list of the sum number of trees logged during each harvest.
  pre-post-cut-number           ;; A list of the number of commercial trees alive before/after each harvest.
  pre-post-cut-volume           ;; A list of the volume (m3) of commercial trees alive before/after each harvest.
]

trees-own [                     ;; TREE VARIABLES
  age                           ;; Age of the tree (yrs).
  alive?                        ;; A Boolean indicating whether a tree is alive (true/false).
  seedling?                     ;; A Boolean indicating whether a tree is a first-year seedling (true/false).
  fall-gap?                     ;; A Boolean indicating whether a tree creates a fall gap (true/false)
  reproduce?                    ;; A Boolean indicating whether a tree is reproductive (true/false).
  diameter                      ;; The diameter (cm) of a tree 1.3 m off the ground (stem diameter).
  basal-diameter                ;; The diameter (cm) of a tree 10 cm off the ground (stem basal diameter).
  basal-area                    ;; The basal area (m2) of a tree, calculated from basal diameter.
  stand-volume                  ;; The standing volume (m3) of a tree, calculated from basal diameter.
  sawn-volume                   ;; The sawn volume (m3) of a tree, calculated from basal diameter.
  growth-rate                   ;; The annual growth rate (cm/yr) of a tree.
  mort-prob                     ;; The probability of mortality for a tree, calculated from diameter and growth.
  fruit-prob                    ;; The probability of fruiting for a tree, calculated from diameter and growth.
  num-fruit                     ;; The number of fruit produced by a tree.
  seedlings                     ;; The number of seedlings produced by a tree.
  e0                            ;; The growth residual in the present year.
  e1                            ;; The growth residual one-year ago.
  e2                            ;; The growth residual two-years ago.
  e3                            ;; The growth residual three-years ago.
  e4                            ;; The growth residual four-years ago.
  e5                            ;; The growth residual five-years ago.
  e6                            ;; The growth residual six-years ago.
  e7                            ;; The growth residual seven-years ago.
  e8                            ;; The growth residual eight-years ago.
  e9                            ;; The growth residual nine-years ago.
  e10                           ;; The growth residual ten-years ago.
]

patches-own [                   ;; PATCH VARIABLES
  disturbance?                  ;; A Boolean indicating whether a patch is a disturbance patch (true/false).
  sweetspot?                    ;; A Boolean indicating whether a patch is a sweetspot patch (true/false).
]

;; MODEL PARAMETERS             ;; CHOSER, SWITCH, AND SLIDER GLOBALS
;; Populations (Listed)         ;; This chooser determines which tree population is used during model simulations.
;; Logging (ON/OFF)             ;; This switch determines whether trees are logged during model simulations.
;; Time (0-150; 5; 100)         ;; This slider determines the maximum length of time (yr) model simulations will run.

;; LOGGING PARAMETERS           ;; ALL DEFAULT STANDARDS FROM GROGAN AND BARRETO (2005).
;; minimum-diameter             ;; The minimum diameter (cm) of trees allowed to be cut for commercial logging (DEFAULT: 60 cm).
;; retention-rate               ;; The minimum retention of commercial trees after logging (DEFAULT: 20% retention = 80% log rate).
;; minimum-density              ;; The minimum allowable density of commercial trees after logging (DEFAULT: 5 trees / 100 ha).
;; cutting-cycle                ;; The number of years between each harvest, a.k.a. the cutting cycle (DEFAULT: 30 yrs).

;; DATA UPLOAD PARAMETERS       ;; LOADS XYD, SHP, AND CSV DATA
```

```
;; File-Name                      ;; The name of the txt, shp, or csv file containing user data.
;; DIAM-Attribute-Name            ;; The name of the diameter attribute in the user shapefile.
;; Site-Width                     ;; The width (x) of the user field site (meters).
;; Site-Height                    ;; The height (y) of the user field site (meters).
;; Patch-Area                     ;; The size (pixels) of patches on the landscape. This determines how large the landscape is drawn.

;; HELPER FUNCTIONS
;; ===================================================================================================

;; These helper functions are used to report values that are calculated in many places throughout the model. A single, centralized
;; copy of a function protects against copy/paste errors.

;; The CALC-E0 helper function calculates the e0 (present-year) growth residual from the other growth residuals. It is used in
;; SETUP-TREE-VALUES, UPDATE-RESIDUALS, and DISPERSE-SEEDS.

to-report calc-e0 [x1 x2 x3 x4 x5 x6 x7 x8 x9 x10]
  report ((0.39916990 * x1) + (0.32081673 * x2) + (0.08135583 * x3) + (-0.04611527 * x4) + (0.13032327 * x5) + (-0.14343649 * x6) +
    (-0.02888621 * x7) + (0.26574481 * x8) + (0.18983354 * x9) + (-0.31121786 * x10) + random-normal 0 growth-sigma)
end

to-report calc-diam [basal-diam]                               ;; This helper function calculates basal diameter from diameter.
  report max (list (0) ((basal-diam - 0.2842709) / 1.1003362)) ;; It is used in CALCULATE-DIAMETER and DISPERSE-SEEDS.
end

to-report calc-basal-diam [diam]                               ;; This helper function calculates diameter from basal diameter.
  report max (list (0) (diam * 1.1003362 + 0.2842709))         ;; It is used in SETUP-TREE-VALUES only (but is still included here).
end

to-report calc-basal-area [diam]                               ;; This helper function calculates basal area from diameter.
  report max (list (0) (pi * (diam / 200) ^ 2))                ;; It is used in SETUP-TREE-VALUES, CALCULATE-DIAMETER, and DISPERSE-SEEDS.
end

to-report calc-stand-volume [diam]                            ;; This helper function calculates standing volume from diameter.
  report max (list (0) (-5.297672 + 0.1263387 * diam))        ;; It is used in SETUP-TREE-VALUES, CALCULATE-DIAMETER, and DISPERSE-SEEDS.
end

to-report calc-sawn-volume [diam]                             ;; This helper function calculates sawn volume from diameter.
  report max (list (0) (-2.697373 + 0.0600342 * diam))        ;; It is used in SETUP-TREE-VALUES, CALCULATE-DIAMETER, and DISPERSE-SEEDS.
end

;; A tree must have a diameter > 41.93 cm to have a positive stand volume. A tree must have a diameter >44.93 cm to have a positive sawn volume.
;; A tree must have a basal diameter > 0.28 cm to have a positive stem diameter. A tree with a positive stem diameter has a positive basal diameter.

;; MODEL SETUP
;; ===================================================================================================

;; Error Check
;; ================================================

;; The ERROR CHECK function is performed whenever the user presses the SETUP or RESIZE buttons. An error check is also performed when
;; the user presses RUN 1 YEAR or RUN X YEARS; the code for these checks is located in the button code.

to error-check
  set errors? false
  if Populations = "" [user-message "A 'Population' must be selected." set errors? true]
  if Populations = "EXAMPLE POPULATIONS" [user-message "A 'Example Population' must be selected." set errors? true]
  if Populations = "USER POPULATIONS" [user-message "A 'User Population' must be selected." set errors? true]
  if Populations = "User Population (xyd)" or  Populations = "User Population (shp)" or Populations = "User Population (csv)" [
    if empty? File-Name [user-message "A 'File-Name' must be specified." set errors? true]
```

```
    if Populations = "User Population (xyd)" [if member? ".txt" File-Name = false [user-message "'File-Name' must be a .txt file." set errors? true]]
    if Populations = "User Population (shp)" [
      if member? ".shp" File-Name = false [user-message "'File-Name' must be a .shp file." set errors? true]
      if empty? DIAM-Attribute-Name [user-message "A 'DIAM-Attribute-Name' must be specified." set errors? true]]
    if Populations = "User Population (csv)" [if member? ".csv" File-Name = false [user-message "'File-Name' must be a .csv file." set errors? true]]
    if Site-Width <= 0 [user-message "'Site-Width' must be a positive non-zero number." set errors? true]
    if Site-Height <= 0 [user-message "'Site-Height' must be a positive non-zero number." set errors? true]
    if Patch-Area <= 0 [user-message "'Patch-Area' must be a positive non-zero number." set errors? true]
  ]
end

;; Set Patch Size
;; =====================================================

to set-patch-area                                                        ;; SETS DEFAULT PATCH AREAS
  if Populations = "SE Pará (204ha)" [set Patch-Area 2.65]              ;; This sets a patch area pre-determined to fit the example
  if Populations = "SE Pará (1035ha)" [set Patch-Area 1.00]             ;; populations inside the model interface; however, the
  if Populations = "Acre/West Amazon" [set Patch-Area 0.65]             ;; patch areas are finicky and resizing may be necessary.

  if Populations = "User Population (xyd)" [set Patch-Area 1.0]         ;; This sets a small patch area for user populations to
  if Populations = "User Population (shp)" [set Patch-Area 1.0]         ;; ensure that the landscape fits within the interface.
  if Populations = "User Population (csv)" [set Patch-Area 1.0]         ;; Resizing will probably be necessary.
end

;; Setup Outline
;; =====================================================

to setup                        ;; SETS UP INITIAL CONDITIONS
  ca                            ;; This clears the NetLogo memory (lists, patches, turtles, etc.).
  setup-globals                 ;; This sets up the values of the constant (global) variables.
  setup-world                   ;; This sets up the world dimensions based on the selected population.
  setup-patches                 ;; This sets up the default forest environment (no disturbance/sweetspot).
  setup-trees                   ;; This sets up the trees based on the selected population.
  setup-dist                    ;; This sets up the parameters for the batch disturbance procedure.
  setup-dist-list               ;; This sets up the disturbance distribution by reading in a file.
  setup-seed-lists              ;; This sets up the seedling size/growth distributions by reading in two files.
  setup-plots                   ;; This sets up the diameter distribution histogram and abundance plot.
  setup-monitors                ;; This sets up the population variables displayed on the interface monitors.
  tick                          ;; This advances the time ticker one-year (Year 0 = setup; Year 1 = harvest).
end

;; Setup Defaults
;; =====================================================

to setup-defaults                           ;; SETS UP DEFAULT HARVEST PARAMETERS AND MODEL PROCEDURE
  set Populations "SE Pará (204ha)"         ;; DEFAULT: SE Pará (204ha) => provides fast/clear simulations
  set Patch-Area 2.75                       ;; DEFAULT: 2.75 pixels => confines the default population to interface
  set Logging true                          ;; DEFAULT: Logging On => most users examine harvest scenarios
  set Time 100                              ;; DEFAULT: 100 years => covers three 30 year logging cycles

  set minimum-diameter 60       ;; DEFAULT: 60 cm diameter (diameter) => current Brazilian standard
  set retention-rate 20         ;; DEFAULT: 20% retention rate => current Brazilian standard
  set minimum-density 5         ;; DEFAULT: 5 trees / 100 ha => current Brazilian standard
  set cutting-cycle 30          ;; DEFAULT: 30 years => current Brazilian standard

  clear-output
  output-print "Press the '?' button next to each section to view descriptions of the section's"
  output-print "features in this definition box. Press 'All Definitions' to review the features"
  output-print "of all the sections."
```

```
end

;; Setup Globals
;; ====================================================

to setup-globals                ;; SETS UP GLOBALS (MODEL CONSTANTS)
  set small-diam 20             ;; The diameter (cm) of the smallest trees tracked during simulations (DEFAULT: 20 cm).
  set growth-sigma 0.4787841    ;; The standard deviation of the growth residual normal distribution (DEFAULT: 0.4787841; Mean = 0; Landis Model).
  set prop-land-dist 0.026      ;; The annual proportion of landscape disturbance (DEFAULT: 0.026; Grogan & Galvão 2006b).
  set no-recruit-dist 10        ;; The distance (m) from a gap edge in which recruitment is impossible (DEFAULT: 10 m; Landis Model).
  set large-dist? false         ;; A Boolean indicating whether large-scale disturbances are implemented during simulations (DEFAULT: false).
  set large-dist-prob 0.025     ;; The probability of a large-scale disturbance occurring (DEFAULT: 1 dist / 40 yrs; Landis Model).
  set large-dist-area 4.0       ;; The area (ha) of large-scale disturbances (DEFAULT: 4 ha; Landis Model).
  set prob-die-standing 0.5     ;; The proportion of dead trees dying standing. 50% create tree fall gaps; 50% remain standing (Landis Model).
  set prob-die-no-repro 0.5     ;; The proportion of dead trees dying before seeding. 50% don't seed after death; 50% seed after death (Landis Model).
  set seed-shadow-area 0.91     ;; The area (ha) of a tree's seed shadow (DEFAULT: 0.91 ha area; 53.8 m radius; Grogan & Galvão 2006b).
  set max-num-fruit 750         ;; The maximum number of fruit per tree (DEFAULT: 750 fruit; Landis Model).
  set seeds-per-fruit 42.4      ;; The average number of seeds per fruit (DEFAULT: 42.4 seeds/fruit; Grogan et al. 2005).
  set establishment-rate 0.085       ;; The proportion of seeds surviving to become first-year seedlings (DEFAULT: 0.085; Grogan & Galvão 2006a).
  set tot-logged-volume (list )      ;; A list of the standing volumes (m3) of trees logged during all previous harvests.
  set cur-logged-volume (list )      ;; A list of the standing volumes (m3) of trees logged during the most recent harvest.
  set annual-harvest-volume (list )  ;; A list of the sum standing volumes (m3) of trees logged during each harvest.
  set annual-harvest-number (list )  ;; A list of the sum number of trees logged during each harvest.
  set pre-post-cut-number (list )    ;; A list of the number of commercial trees alive before/after each harvest.
  set pre-post-cut-volume (list )    ;; A list of the volume (m3) of commercial trees alive before/after each harvest.

;; site-area                         ;; This variable is setup below because it requires a few lines of code.
;; disturbance-data                  ;; This variable is setup below because it requires a few lines of code.
;; seed-diam-data                    ;; This variable is setup below because it requires a few lines of code.
;; seed-growth-data                  ;; This variable is setup below because it requires a few lines of code.
end

;; Setup World
;; ====================================================

to setup-world                                              ;; SETS UP WORLD DIMENSIONS
  let new+x round (Site-Width / 10 - 1) / 2                 ;; These functions calculate the dimensions of the NetLogo world based on the dimensions
  let new-x round (Site-Width / 10 - 1) / 2 * (-1)          ;; of the user-provided field site. The site dimensions are provided in meters so they
  let new+y round (Site-Height / 10 - 1) / 2                ;; are divided by 10 to convert from meters to patches, reduced by 1 to account for the
  let new-y round (Site-Height / 10 - 1) / 2 * (-1)         ;; 0 row/column, and divided by 2 since NetLogo uses +/- coordinates.

  if Populations = "SE Pará (204ha)" [resize-world -63 63 -88 88 set-patch-size Patch-Area]        ;; The dimensions of the example populations
  if Populations = "SE Pará (1035ha)" [resize-world -162 162 -175 175 set-patch-size Patch-Area]   ;; were calculated manually ( this work is
  if Populations = "Acre/West Amazon" [resize-world -246 246 -110 110 set-patch-size Patch-Area]   ;; shown in the header above).

  if Populations = "User Population (xyd)" [resize-world new-x new+x new-y new+y set-patch-size Patch-Area]    ;; The user populations are drawn
  if Populations = "User Population (shp)" [resize-world new-x new+x new-y new+y set-patch-size Patch-Area]    ;; using the default patch area and
  if Populations = "User Population (csv)" [resize-world new-x new+x new-y new+y set-patch-size Patch-Area]    ;; the dimensions calculated above.

  if Populations = "SE Pará (204ha)" [set site-area 204]        ;; The example populations use fixed site areas because fitting the sites inside
  if Populations = "SE Pará (1035ha)" [set site-area 1035]      ;; a rectangular world creates spaces between the site and world boundaries. These
  if Populations = "Acre/West Amazon" [set site-area 685]       ;; spaces increase the site area and reduce the reported tree density.

  if Populations = "User Population (xyd)" [set site-area count patches / 100]   ;; The area of user-defined sites is calculated as the area of
  if Populations = "User Population (shp)" [set site-area count patches / 100]   ;; the NetLogo world (rectangular box) because allowing the user
  if Populations = "User Population (csv)" [set site-area count patches / 100]   ;; to submit site areas would invite too many user errors.
end

;; Setup Landscape
```

```
;; ==================================================

to setup-patches                 ;; SETS UP INITIAL PATCH ENVIRONMENT
  ask patches [                  ;; The default landscape is colored green with no
    set disturbance? false       ;; disturbances or sweetspot areas as these are
    set sweetspot? false         ;; added to the landscape by the disturbance procedure.
    set pcolor green             ;; The patches are reset between every year (time step).
  ]
end

;; Setup Trees Outline
;; ==================================================

to setup-trees                                                ;; SETS UP THE DIFFERENT TREE POPULATIONS
  if Populations = "SE Pará (204ha)" [setup-mara-204-trees]    ;; This sets up the 204ha Pará mahogany population (Grogan 2001).
  if Populations = "SE Pará (1035ha)" [setup-mara-1035-trees]  ;; This sets up the 1035ha Pará mahogany population (Grogan 2001).
  if Populations = "Acre/West Amazon" [setup-acre-trees]       ;; This sets up the Acre/West Amazon mahogany population (Grogan et al. 2008).

  if Populations = "User Population (xyd)" [setup-xyd-trees]   ;; This sets up a population based on a user txt-file with xy and diameter data.
  if Populations = "User Population (shp)" [setup-shp-trees]   ;; This sets up a population based on a user shp-file with xy and diameter data.
  if Populations = "User Population (csv)" [setup-csv-trees]   ;; This sets up a population based on a user csv-file with diameter data.
end

;; Setup Trees Details
;; ==================================================

to setup-mara-204-trees                                                       ;; SETS UP TREES - MARAJOARA 204HA PLOT
  let mara-204-tree-data gis:load-dataset "Data/mara-204-tree-data.shp"         ;; This stores GIS tree data in a NetLogo list.
  let mara-204-stream-data gis:load-dataset "Data/mara-204-stream-data.shp"     ;; This stores GIS stream data in a NetLogo list.
  let mara-204-boundary-data gis:load-dataset "Data/mara-204-boundary-data.shp" ;; This stores GIS boundary data in a NetLogo list.
  let mara-204-world-data gis:load-dataset "Data/mara-204-world-data.shp"       ;; This stores GIS world data in a NetLogo list.
  gis:set-world-envelope (gis:envelope-of mara-204-world-data)                  ;; This sets the extent of the NetLogo world

  gis:set-drawing-color white                                                   ;; This draws the field site boundary in
  gis:draw mara-204-boundary-data 2                                             ;; white with a line thickness of two.
  gis:set-drawing-color blue                                                    ;; This draws the stream systems in blue
  gis:draw mara-204-stream-data 2                                               ;; with a line thickness of two.

  foreach gis:feature-list-of mara-204-tree-data [                              ;; This reads each row of the GIS shapefile, creates
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))       ;; a tree at the specified coordinates, and gives
    create-trees 1 [                                                            ;; the tree its listed diameter. SETUP-TREE-VALUES
      set xcor item 0 location                                                  ;; sets up the remaining tree values.
      set ycor item 1 location
      set diameter gis:property-value ? "DM94"
      setup-tree-values
    ]
  ]
end

to setup-mara-1035-trees                                                        ;; SETS UP TREES - MARAJOARA 1035HA PLOT
  let mara-1035-tree-data gis:load-dataset "Data/mara-1035-tree-data.shp"         ;; This stores GIS tree data in a NetLogo list.
  let mara-1035-stream-data gis:load-dataset "Data/mara-1035-stream-data.shp"     ;; This stores GIS stream data in a NetLogo list.
  let mara-1035-boundary-data gis:load-dataset "Data/mara-1035-boundary-data.shp" ;; This stores GIS boundary data in a NetLogo list.
  let mara-1035-world-data gis:load-dataset "Data/mara-1035-world-data.shp"       ;; This stores GIS world data in a NetLogo list.
  gis:set-world-envelope (gis:envelope-of mara-1035-world-data)                   ;; This sets the extent of the NetLogo world

  gis:set-drawing-color white                                                     ;; This draws the field site boundary in
  gis:draw mara-1035-boundary-data 1                                              ;; white with a line thickness of one.
  gis:set-drawing-color blue                                                      ;; This draws the stream systems in blue
```

```
  gis:draw mara-1035-stream-data 1                                                  ;; with a line thickness of one.

  foreach gis:feature-list-of mara-1035-tree-data [                                 ;; This reads each row of the GIS shapefile, creates
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))            ;; a tree at the specified coordinates, and gives
    create-trees 1 [                                                                ;; the tree its listed diameter. SETUP-TREE-VALUES
      set xcor item 0 location                                                      ;; sets up the remaining tree values.
      set ycor item 1 location
      set diameter gis:property-value ? "DBH"
      setup-tree-values
    ]
  ]
end

to setup-acre-trees                                                                 ;; SETS UP TREES - ACRE/WEST AMAZON PLOT
  let acre-tree-data gis:load-dataset "Data/acre-tree-data.shp"                     ;; This stores GIS tree data in a NetLogo list.
  let acre-boundary-data gis:load-dataset "Data/acre-boundary-data.shp"             ;; This stores GIS boundary data in a NetLogo list.
  let acre-world-data gis:load-dataset "Data/acre-world-data.shp"                   ;; This stores GIS world data in a NetLogo list.
  gis:set-world-envelope (gis:envelope-of acre-world-data)                          ;; This sets the extent of the NetLogo world

  gis:set-drawing-color white                                                       ;; This draws the field site boundary in white
  gis:draw acre-boundary-data 1                                                     ;; with a line thickness of one.

  foreach gis:feature-list-of acre-tree-data [                                      ;; This reads each row of the GIS shapefile, creates
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))            ;; a tree at the specified coordinates, and gives
    create-trees 1 [                                                                ;; the tree its listed diameter. SETUP-TREE-VALUES
      set xcor item 0 location                                                      ;; sets up the remaining tree values.
      set ycor item 1 location
      set diameter gis:property-value ? "DIAM"
      setup-tree-values
    ]
  ]
end

to setup-xyd-trees                            ;; SETS UP TREES - USER SPATIAL DIAMETER (TXT) POPULATION
  let x-list (list )                          ;; This makes a list for storing the x-coordinates from the user file.
  let y-list (list )                          ;; This makes a list for storing the y-coordinates from the user file.
  let diam-list (list )                       ;; This makes a list for storing the diameters from the user file.

  file-open (word "User/" File-Name)          ;; This opens the file designated by the user in the FILE-NAME prompt.
  while [not file-at-end?][                   ;; This reads the file from the beginning to the end.
    set x-list fput file-read x-list          ;; This puts the x-coordinates in the x-list (file must be: x, y, diam).
    set y-list fput file-read y-list          ;; This puts the y-coordinates in the y-list.
    set diam-list fput file-read diam-list    ;; This puts the diameter values in the diam-list.
  ]
  file-close                                  ;; This closes the file designated by the user in the FILE-NAME prompt.

  let xmin min x-list                         ;; This calculates the minimum x-coordinate value.
  let xmax max x-list                         ;; This calculates the maximum x-coordinate value.
  let ymin min y-list                         ;; This calculates the minimum y-coordinate value.
  let ymax max y-list                         ;; This calculates the maximum y-coordinate value.

  (foreach x-list y-list diam-list [                                        ;; This code loops through the x-, y-, and diam- lists to
      create-trees 1 [                                                      ;; create a tree with each set of x, y, and diameter values.
        let pre-xcor (?1 - xmin) / (xmax - xmin) * world-width + min-pxcor  ;; The code translates the xy coordinates from spherical
        let pre-ycor (?2 - ymin) / (ymax - ymin) * world-height + min-pycor ;; coordinates to NetLogo coordinates; however, because the
        let add-xcor (pre-xcor / abs pre-xcor * -1)                         ;; population is contained within a box, the "pre" coordinates
        let add-ycor (pre-ycor / abs pre-ycor * -1)                         ;; place some trees on the world edge. The "add" calculations
        set xcor pre-xcor + add-xcor                                        ;; scale the population inwards to prevent edge trees.
        set ycor pre-ycor + add-ycor                                        ;; SETUP-TREE-VALUES sets up the remaining tree values.
```

```
      set diameter ?3
      setup-tree-values
    ]
  ])
end

to setup-shp-trees                                                        ;; SETS UP TREES - USER SPATIAL DIAMETER (SHP) POPULATION
  let shp-tree-data gis:load-dataset (word "User/" File-Name)             ;; This code reads the user-provided shapefile into NetLogo and sets
  let tree-envelope gis:envelope-of shp-tree-data                         ;; an initial envelope equal to the extent of the user population. A
  let x-expansion (item 1 tree-envelope - item 0 tree-envelope) * 0.0001  ;; horizontal (x) and vertical (y) expansion factor are calculated
  let y-expansion (item 3 tree-envelope - item 2 tree-envelope) * 0.0001  ;; to pad the world envelope so trees won't fall on the world edge.

  let expanded-envelope (list                                             ;; A GIS envelope is the following (list): minimum-x, maximum-x,
    (item 0 tree-envelope - x-expansion)(item 1 tree-envelope + x-expansion)  ;; minimum-y, maximum-y. Each of these items is padded with the
    (item 2 tree-envelope - y-expansion)(item 3 tree-envelope + y-expansion)) ;; appropriate expansion factor and the new min's and max's become
  gis:set-world-envelope expanded-envelope                                ;; the min's and max's for the new envelope.

  foreach gis:feature-list-of shp-tree-data [                             ;; This code reads the XY coordinates of each feature (tree) in the
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))  ;; user shapefile into the LOCATION list and creates a tree at this
    create-trees 1 [                                                      ;; location in the NetLogo world. Each tree receives a diameter from
      set xcor item 0 location                                            ;; the attribute in the shapefile with the user-defined name.
      set ycor item 1 location                                            ;; SETUP-TREE-VALUES sets up the remaining tree values.
      set diameter gis:property-value ? (word DIAM-Attribute-Name)
      setup-tree-values
    ]
  ]
end

to setup-csv-trees                                                        ;; SETS UP TREES - USER NON-SPATIAL DIAMETER (TXT) POPULATION
  let csv-tree-data (list )                                               ;; This code opens a user-provided csv file containing non-spatial
  file-open (word "User/" File-Name)                                      ;; diameter data and reads the diameters into a NetLogo list.
  while [not file-at-end?][set csv-tree-data fput file-read csv-tree-data]
  file-close
  foreach csv-tree-data [                                                 ;; This code creates a tree with each diameter in the diameter list.
    create-trees 1 [                                                      ;; The trees are given random coordinates (b/c no spatial data).
      setxy random-xcor random-ycor                                       ;; SETUP-TREE-VALUES sets up the remaining tree values.
      set diameter ?
      setup-tree-values
    ]
  ]
end

to setup-tree-values                                                      ;; SETS TREES VARIABLES
  set basal-diameter calc-basal-diam diameter                             ;; Basal diameter (cm) calculated from diameter.
  set basal-area calc-basal-area diameter                                 ;; Basal area (m2) calculated from diameter.
  set stand-volume calc-stand-volume diameter                             ;; Standing volume (m3) calculated from diameter.
  set sawn-volume calc-sawn-volume diameter                               ;; Sawn volume (m3) calculated from diameter.
  set size 1 + diameter / 50                                              ;; Trees are sized based on diameter.
  set shape "tree"                                                        ;; Trees are shaped as "trees".
  set color green - 3                                                     ;; Trees are colored green.
  set age 1000                                                            ;; Age of initial trees is unknown.
  set alive? true                                                         ;; All initial trees are alive.
  set seedling? false                                                     ;; No initial trees are seedlings.
  set reproduce? true                                                     ;; All initial trees are potentially reproductive.
  set fall-gap? false                                                     ;; No initial trees create fall gaps (still alive).
  set growth-rate 0                                                       ;; Growth rate initially 0 because it is set later.
  set mort-prob 0                                                         ;; Mortality rate initially 0 because it is set later.
  set fruit-prob 0                                                        ;; Fruiting probability initially 0 because it is set later.
  set num-fruit 0                                                         ;; Number of fruit initially 0 because it is set later.
```

```
  set seedlings 0                                                                  ;; Seedlings initially 0 because it is set later.
  set e10 random-normal 0 growth-sigma                                             ;; Tenth-year residual is randomly selected.
  set e9 random-normal 0 growth-sigma                                              ;; Ninth-year residual is randomly selected.
  set e8 random-normal 0 growth-sigma                                              ;; Eighth-year residual is randomly selected.
  set e7 random-normal 0 growth-sigma                                              ;; Seventh-year residual is randomly selected.
  set e6 random-normal 0 growth-sigma                                              ;; Sixth-year residual is randomly selected.
  set e5 random-normal 0 growth-sigma                                              ;; Fifth-year residual is randomly selected.
  set e4 random-normal 0 growth-sigma                                              ;; Fourth-year residual is randomly selected.
  set e3 random-normal 0 growth-sigma                                              ;; Third-year residual is randomly selected.
  set e2 random-normal 0 growth-sigma                                              ;; Second-year residual is randomly selected.
  set e1 random-normal 0 growth-sigma                                              ;; First-year residual is randomly selected.
  set e0 calc-e0 e1 e2 e3 e4 e5 e6 e7 e8 e9 e10                                    ;; Present-year residual is calculated from e1-e10.
end

;; A tree must have a diameter > 41.93 cm to have a positive stand volume. A tree must have a diameter >44.93 cm to have a positive sawn volume.
;; A tree must have a basal diameter > 0.28 cm to have a positive stem diameter. A tree with a positive stem diameter has a positive basal diameter.

;; Setup Batch Disturbance Parameters
;; ==================================================

to setup-dist
  let prop-dist-reduce 0.8            ;; This determines the proportion of landscape disturbance to be done in batch.
  let mean-dist-area 110.385655       ;; This is the mean area (m2) of disturbances drawn from the disturbance gamma distribution.
  let true-area count patches / 100   ;; This is the area (ha) of the entire landscape (larger than the field site area).

  let batch-dist-reduce 0.93                          ;; The number of disturbance patches must be reduced again for safety. Too many
  if true-area <= 1000 [set batch-dist-reduce 0.90]   ;; disturbances in small sites can results in over disturbance; therefore, the extent of
  if true-area <= 750 [set batch-dist-reduce 0.85]    ;; the reduction depends on site size. Larger sizes reduce the batch disturbance number
  if true-area <= 500 [set batch-dist-reduce 0.80]    ;; less than smaller sites. The largest sites (>1000ha) reduce the batch disturbance
  if true-area <= 200 [set batch-dist-reduce 0.70]    ;; number by only 7%, 93% of the original value.
  if true-area <= 50 [set batch-dist-reduce 0.50]

  set num-batch-dist (((true-area * 10000) * prop-land-dist * prop-dist-reduce) / mean-dist-area) * batch-dist-reduce
end

;; Setup Disturbance & Seedling Diameter Lists
;; ==================================================

to setup-dist-list                                                                   ;; READS IN DISTURBANCE DATA
  set disturbance-data (list )                                                       ;; File opened, file read, file closed.
  file-open "Data/gap-data.csv"                                                      ;; This data is not actually used in the model but is made
  while [not file-at-end?][set disturbance-data fput file-read disturbance-data]     ;; available to the user. The disturbance gamma distribution
  file-close                                                                         ;; function is based on this data (gaps = circles in m2).
end

to setup-seed-lists                                                                  ;; READS IN SEEDLING DIAM & GROWTH LISTS
  set seed-diam-data (list )                                                         ;; File opened, file read, file closed.
  file-open "Data/seed-diam-data.csv"                                                ;; This data is used to randomly assign new seedlings
  while [not file-at-end?][set seed-diam-data fput file-read seed-diam-data]         ;; a diameter. Diameters are basal diameters in cm.
  file-close

  set seed-growth-data (list )                                                       ;; File opened, file read, file closed.
  file-open "Data/seed-growth-data.csv"                                              ;; This data is used to randomly assign new seedlings
  while [not file-at-end?][set seed-growth-data fput file-read seed-growth-data]     ;; a growth rate. Growth rates are measured in cm/yr.
  file-close
end

;; Setup Plots
;; ==================================================
```

```
to setup-plots                                                          ;; SETS UP PLOTS
  set-current-plot "Diameter Distribution"                              ;; This section sets up the diameter distribution histogram
    set-plot-x-range (0) (max [diameter] of trees)                      ;; in the initial year. The initial year x-axis (diameter)
    set-plot-y-range (0) (25)                                           ;; extends from 0 to the maximum diameter of trees in the
      set-current-plot-pen "Year 0 Histogram"                           ;; current population. The initial year y-axis (frequency)
        set-plot-pen-mode 1                                             ;; extends from 0 to 25. The initial year size-distribution,
        set-plot-pen-interval 10                                        ;; shown in black, plots only trees larger than the SMALL-DIAM
        set-plot-pen-color black                                        ;; into 10 cm diameter bins. A vertical gray line marking
        histogram [diameter] of trees with [diameter >= small-diam]     ;; commercial-size extends from 0 to the maximum y-value.
      set-current-plot-pen "Commercial-Size Marker"
        set-plot-pen-mode 0
        set-plot-pen-color gray
        plotxy minimum-diameter 0
        plotxy minimum-diameter plot-y-max

  set-current-plot "Tree Density"                                       ;; This section sets up the density plot in the initial year.
    set-plot-x-range (0) (Time)                                         ;; The initial year x-axis (time) extends from 0 to the run time
    set-plot-y-range (0) (round (count trees / site-area * 100 + 10))   ;; value designated by the user. The initial y-axis (density)
      set-current-plot-pen "Total Trees"                                ;; extends from 0 to the current density of trees plus ten more.
        set-plot-pen-mode 0                                             ;; The density of trees larger than the SMALL-DIAM are plotted
        set-plot-pen-color black                                        ;; in black. The density of trees larger than commercial-size
        plot count trees with [diameter >= small-diam] / site-area * 100  ;; are plotted in red. The harvest years are marked by a vertical
      set-current-plot-pen "Commercial Trees"                           ;; gray line extending from 0 to the maximum y-value.
        set-plot-pen-mode 0
        set-plot-pen-color red
        plot count trees with [diameter >= minimum-diameter] / site-area * 100
      set-current-plot-pen "Harvest Year Marker"
        let harvest-years n-values (floor (Time / cutting-cycle) + 1) [(?1) * cutting-cycle + 1]
        foreach harvest-years [
          set-plot-pen-mode 0
          set-plot-pen-color gray
          plot-pen-up
          plotxy ?1 0
          plot-pen-down
          plotxy ?1 plot-y-max
        ]
end

to update-plots                                                         ;; UPDATES PLOTS
  set-current-plot "Diameter Distribution"                              ;; This section updates the plots every year (time step).
    set-current-plot-pen "Current Year Histogram"                       ;; This code controls updates to the size distribution
      set-plot-pen-mode 1                                               ;; histogram. The current size-distribution, shown in red,
      set-plot-pen-interval 10                                          ;; plots only trees larger than the SMALL-DIAM into 10 cm
      set-plot-pen-color red                                            ;; diameter bins. The vertical gray line marking commercial-size
      histogram [diameter] of trees with [diameter >= small-diam]       ;; is redrawn each year (time step) and extends from 0 to
    set-current-plot-pen "Commercial-Size Marker"                       ;; the maximum y-value.
      set-plot-pen-mode 0
      set-plot-pen-color gray
      plotxy minimum-diameter 0
      plotxy minimum-diameter plot-y-max

  set-current-plot "Tree Density"                                       ;; This code controls updates to the density plot. The density
      set-current-plot-pen "Total Trees"                                ;; of all trees larger than the SMALL-DIAM is plotted in black.
        set-plot-pen-mode 0                                             ;; The density of trees larger than commercial-size is plotted
        set-plot-pen-color black                                        ;; in red. The harvest year markers (vertical grey lines) are
        plot count trees with [diameter >= small-diam] / site-area * 100  ;; redrawn each year and extend from 0 to the maximum y-value
      set-current-plot-pen "Commercial Trees"                           ;; at each of the harvest years.
        set-plot-pen-mode 0
```

```
        set-plot-pen-color red
        plot count trees with [diameter >= minimum-diameter] / site-area * 100
      set-current-plot-pen "Harvest Year Marker"
        let harvest-years n-values (floor (Time / cutting-cycle) + 1) [(?1) * cutting-cycle + 1]
        foreach harvest-years [
          set-plot-pen-mode 0
          set-plot-pen-color gray
          plot-pen-up
          plotxy ?1 0
          plot-pen-down
          plotxy ?1 plot-y-max
        ]
end

;; Setup Monitors
;; ==================================================

;; This code sets up the initial population variables (total/commercial density and commercial volume)
;; shown in the monitors on the model interface.

to setup-monitors
  set y0-tree-density count trees with [diameter >= small-diam] / site-area * 100
  set y0-comm-density count trees with [diameter >= minimum-diameter] / site-area * 100
  set y0-comm-volume sum [stand-volume] of trees with [diameter >= minimum-diameter]

  output-print "Press the '?' button next to each section to view descriptions of the section's"
  output-print "features in this definition box. Press 'All Definitions' to review the features"
  output-print "of all the sections."
end

;; RUN MODEL
;; ====================================================================================================

;; Model Outline
;; ==================================================

to run-model                                ;; MODEL PROCEDURE
  if ticks > Time [stop]                    ;; The model stops running if the stop time is violated.
  if count trees = 0 [stop]                 ;; The model stops running if all the trees die.
  log-trees-init                            ;; This procedure logs trees in Year 0 if logging is turned on.
  reset-trees                               ;; This procedure resets certain tree values before each run.
  grow-trees                                ;; This procedure grows trees using growth autocorrelation.
  log-trees                                 ;; This procedure logs trees according to user-defined parameters.
  kill-trees                                ;; This procedure kills trees based on growth and diameter.
  disturb-trees                             ;; This procedure disturbs the landscape based on the disturbance parameters.
  reproduce-trees                           ;; This procedure reproduces trees and disperses seeds on the landscape.
  remove-trees                              ;; This procedure removes dead trees from the landscape.
  remove-gaps                               ;; This procedure removes disturbances from the landscape.
  update-plots                              ;; This procedure updates the size-distribution and abundance plots.
  tick                                      ;; This advances the ticker one time step (one year).
end

;; Grow Trees Outline
;; ==================================================

to grow-trees                               ;; GROWTH PROCEDURE
  ask trees [set age age + 1]               ;; This procedure ages the trees one year.
  update-residuals                          ;; This procedure updates the growth residuals.
  calculate-growth                          ;; This procedure calculates the new growth rate from the previous growth rate and residuals.
```

```
  calculate-diameter                       ;; This procedure calculates the new diameter from the new growth rate.
end

;; Grow Trees Details
;; ==================================================

to update-residuals                        ;; UPDATES RESIDUALS
  ask trees [                              ;; Each residual falls back one year.
    set e10 e9                             ;; The e0 residual is calculated from the other residuals.
    set e9 e8
    set e8 e7
    set e7 e6
    set e6 e5
    set e5 e4
    set e4 e3
    set e3 e2
    set e2 e1
    set e1 e0
    set e0 calc-e0 e1 e2 e3 e4 e5 e6 e7 e8 e9 e10
  ]
end

to calculate-growth                                                       ;; CALCULATES GROWTH RATE
  ask trees [                                                             ;; Growth rates (cm/yr) are calculated from basal diameter.
    set growth-rate (0.420426053 + (basal-diameter * 0.006911997) -      ;; Growth rates must be greater than or equal to zero.
        (0.008807226 * max (list (0) (basal-diameter - 40))) + e0)
    if growth-rate < 0 [set growth-rate 0]
  ]
end

to calculate-diameter                                                     ;; UPDATES DIAMETER, AREA, AND VOLUME
  ask trees [                                                             ;; This code uses the helper functions to
    set basal-diameter (growth-rate + basal-diameter)                     ;; update the standard tree size measures.
    set diameter calc-diam basal-diameter                                 ;; Diameter (cm) is calculated from basal diameter.
    set basal-area calc-basal-area diameter                               ;; Basal area (m2) is calculated from diameter.
    set stand-volume calc-stand-volume diameter                           ;; Standing volume (m3) is calculated from diameter.
    set sawn-volume calc-sawn-volume diameter                             ;; Sawn volume (m3) is calculated from diameter.
    set size 1 + diameter / 50
  ]
end

;; Log Trees
;; ==================================================

to log-trees-init                                               ;; LOG TREES IN YEAR 1
  if Logging = true and ticks = 1 [harvest-trees]               ;; This code is separated from the other logging code because it occurs
end                                                             ;; before growth (logging occurs after growth in all other years).

to log-trees                                                                    ;; LOG TREES IN HARVEST YEARS
  let harvest-year? false                                                       ;; This code determines whether the current year is a harvest
  let num-harvests floor (Time / cutting-cycle)                                 ;; year by comparing the current year (ticks) to the list of
  let harvest-years n-values num-harvests [(?1 + 1) * cutting-cycle + 1]        ;; harvest years (HARVEST-YEARS). If the current year is a
  if member? ticks harvest-years [set harvest-year? true]                       ;; harvest year and logging is turned on, trees are logged
  if Logging = true and harvest-year? = true [harvest-trees]                    ;; using the harvest-trees function.
end

to harvest-trees                                                                ;; HARVEST PROCEDURE
  set cur-logged-volume (list )                                                 ;; The first steps are to: (1) setup the logged volume list;
  let log-rate (1 - (retention-rate / 100))                                     ;; (2) calculate the LOG-RATE as a decimal; (3) identify and
```

```
let comm-trees trees with [diameter >= minimum-diameter]                ;; count the commercial trees; and (4) determine the maximum
let num-comm-trees (count comm-trees)                                   ;; harvest size using the log-rate.
let max-num-cut floor (log-rate * num-comm-trees)

let current-density num-comm-trees / site-area * 100                              ;; This code calculates density following harvest
let post-max-cut-density (((num-comm-trees - max-num-cut) / site-area) * 100)     ;; at the LOG-RATE and calculates the difference
let density-differential (minimum-density - post-max-cut-density)                 ;; between this POST-MAX-CUT-DENSITY and the minimum
let count-differential ((density-differential / 100) * site-area)                 ;; allowable density. This information is used to
let max-legal-cut min (list (max-num-cut) (floor (max-num-cut - count-differential)))   ;; calculate the actual maximum legal cut.

if current-density > minimum-density [                                            ;; Harvest occurs only if the current density is greater
  let comm-trees-sort (list )                                                     ;; than the minimum density. The harvest is randomly
  set comm-trees-sort sort comm-trees                                             ;; stratified within ~15 tree strata. This code sorts
  set comm-trees-sort sort-by [[diameter] of ?1 < [diameter] of ?2] comm-trees-sort     ;; the trees by diameter before creating the strata.

  let bin-size 15                                                       ;; This code stratifies the trees according to diameter size class
  let strata-list (list )                                               ;; by creating strata of the specified bin-size. Most strata will
  let num-strata ceiling (num-comm-trees / bin-size)                    ;; contain 15 trees - an overflow bin captures the remaining trees.

  foreach n-values num-strata [?] [                                     ;; Although initially ordered by diameter, the trees are ultimately
    let new-strata sublist comm-trees-sort (? * bin-size)               ;; shuffled to randomize logging within the strata. Each strata, a
      (min (list (? * bin-size + bin-size) (length comm-trees-sort)))   ;; list of trees of similar diameters, is stored in a list for later.
    set new-strata shuffle new-strata
    set strata-list lput new-strata strata-list
  ]

  let log-rate-part (max-num-cut - count-differential) / num-comm-trees   ;; This code determines whether trees will be harvested at a full or
  let log-rate-final min (list (log-rate) (log-rate-part))                ;; partial LOG-RATE; this depends on the minimum density parameter.

  let log-tree-list (list )                                 ;; This code determines which trees are logged from each strata. It calculates the
  foreach strata-list [                                     ;; number of trees to log from each strata (NUM-REMOVE) and records the identity
    let num-remove (round (length ? * log-rate-final))      ;; of the first NUM-REMOVE trees in the LOGGED-TREES list. The LOGGED-TREES lists
    let logged-trees (sublist ? 0 num-remove)               ;; for each strata are combined in the LOG-TREE-LIST.
    set log-tree-list lput logged-trees log-tree-list
  ]

  set log-tree-list reduce [sentence ?1 ?2] log-tree-list    ;; This code reduces the LOG-TREE-LIST, a list of lists, into a single list. If the
  if length log-tree-list > max-legal-cut [                  ;; list contains more trees than allowed by MAX-LEGAL-CUT (an artifact of using the
    let difference (length log-tree-list - max-legal-cut)    ;; LOG-RATE percentage to count cut trees), a random tree is removed from the list.
    repeat difference [set log-tree-list remove-item (random length log-tree-list) log-tree-list]
  ]

  if length log-tree-list < max-legal-cut [                  ;; This code randomly adds an unlogged commercial tree to the LOG-TREE-LIST if
    let difference (max-legal-cut - length log-tree-list)    ;; more trees can be harvested. I'm not positive this is ever necessary.
    repeat difference [set log-tree-list lput (one-of comm-trees with [member? self log-tree-list = false]) (log-tree-list)]
  ]

  let comm-trees-alive comm-trees with [alive? = true]                                              ;; This code records the number and
  set pre-post-cut-number lput count comm-trees-alive pre-post-cut-number                           ;; volume of commercial-size trees
  set pre-post-cut-volume lput (precision (sum [stand-volume] of comm-trees-alive) 1) pre-post-cut-volume   ;; immediately before logging.

  ask turtle-set log-tree-list [                                            ;; This code converts the logged tree list into an agentset
    set alive? false                                                        ;; All logged trees create tree fall gaps (all logged trees
    set fall-gap? true                                                      ;; fall) and all logged trees are marked as dead. 50% of logged
    set tot-logged-volume fput (precision stand-volume 1) tot-logged-volume    ;; trees are given the opportunity to reproduce. The volume of
    set cur-logged-volume fput (precision stand-volume 1) cur-logged-volume    ;; the logged trees are recorded in the lists responsible for
    if random-float 1 < prob-die-no-repro [set reproduce? false]            ;; tracking the current harvest volume and entire cycle volume.
  ]
```

```
    set annual-harvest-number lput length cur-logged-volume annual-harvest-number            ;; Adds sum number of trees harvested to list end.
    set annual-harvest-volume lput (precision sum cur-logged-volume 1) annual-harvest-volume  ;; Adds sum volume of trees harvested to list end.

    set comm-trees-alive comm-trees with [alive? = true]                                        ;; This code records the number and
    set pre-post-cut-number lput count comm-trees-alive pre-post-cut-number                     ;; volume of commercial-size trees
    set pre-post-cut-volume lput (precision (sum [stand-volume] of comm-trees-alive) 1) pre-post-cut-volume   ;; immediately after logging.
  ]
end

;; Kill Trees
;; ==================================================

to kill-trees
  ask trees with [alive? = true] [
    let kill-odds (-0.083 - (4.177 * growth-rate) + (3.705 * max (list (0) (growth-rate - 0.4))) + (2.57 * max (list (0) (growth-rate - 1.5)))
      - (0.5753 * basal-diameter) + (0.5544 * max (list (0) (basal-diameter - 5))) + (0.0270 * max (list (0) (basal-diameter - 25))) +
      (0.00077 * max (list (0) (basal-diameter - 85))))

    set mort-prob ((exp kill-odds) / (1 + (exp kill-odds)))                  ;; KILL PROCEDURE
    if random-float 1 < mort-prob [                                           ;; The probability of mortality is calculated from the logit
      set alive? false                                                        ;; transformation of the "kill-odds" (log-odds). 50% of trees
      if random-float 1 < prob-die-standing [set fall-gap? true]              ;; marked for death create tree fall gaps and 50% are given
      if random-float 1 < prob-die-no-repro [set reproduce? false]            ;; the opportunity to reproduce. Dead trees are removed later.
    ]
  ]
end

;; Disturb Trees
;; ==================================================

to disturb-trees      ;; DISTURBANCE PROCEDURE
  batch-disturb       ;; Places initial batch of disturbances on landscape (all disturbances at once).
  final-disturb       ;; Places disturbances on landscape one at a time until disturbance proportion is satisfied.
  crt-fall-gaps       ;; Builds gaps around dead trees that fall (logged trees and 50% naturally dead trees)
  large-disturb       ;; Places a large disturbance on landscape if the large disturbance function is turned on.
end


to batch-disturb                                              ;; BATCH DISTURBANCE PROCEDURE
  ask n-of num-batch-dist patches [                           ;; This procedure draws the batch disturbances from a gamma
    let alpha 0.6127423153                                    ;; distribution and builds the disturbances on the landscape,
    let lambda 0.0055509234                                   ;; all at once. The number of disturbances drawn, determined
    let dist-area random-gamma alpha lambda                   ;; above, is a function of the site area. Disturbances are
    let dist-radius (sqrt (dist-area / pi))                   ;; built in a random locations and the sweetspot is built inside.
    let sweet-radius (dist-radius - no-recruit-dist)
    ask patches in-radius (dist-radius / 10) with [disturbance? = false] [set disturbance? true set pcolor red]
    if sweet-radius > 0 [ask patches in-radius (sweet-radius / 10) with [sweetspot? = false] [set sweetspot? true set pcolor red - 2]]
  ]

  let dist-patch-goal prop-land-dist * count patches                 ;; This code notifies the user if the batch disturbance procedure
  let dist-patch-true count patches with [disturbance?]              ;; over disturbs the landscape. This happens occasionally on small
  if dist-patch-true > dist-patch-goal [                             ;; landscapes.
    let prop-dist precision (dist-patch-true / count patches) 4
    let perc-diff precision ((dist-patch-true / dist-patch-goal - 1) * 100) 1
    print (word "In Year " ticks ", " prop-dist " of the landscape was disturbed, which exceeds the target proportion by " perc-diff "%.")
  ]
end

to final-disturb                                              ;; FINAL DISTURBANCE PROCEDURE
```

```
  let dist-patch-now count patches with [disturbance?]         ;; This procedure adds new disturbances, each drawn from a gamma
  while [dist-patch-now < (prop-land-dist * count patches)][   ;; distribution, one at a time, until 2.6% (PROP-LAND-DIST) of the
    ask one-of patches [                                       ;; landscape is disturbed. Disturbances are created in a random
      let alpha 0.6127423153                                   ;; location and the sweetspot is built inside.
      let lambda 0.0055509234
      let dist-area random-gamma alpha lambda
      let dist-radius (sqrt (dist-area / pi))
      let sweet-radius (dist-radius - no-recruit-dist)
      ask patches in-radius (dist-radius / 10) with [disturbance? = false] [set disturbance? true set pcolor red]
      if sweet-radius > 0 [ask patches in-radius (sweet-radius / 10) with [sweetspot? = false] [set sweetspot? true set pcolor red - 2]]
      set dist-patch-now count patches with [disturbance?]
    ]
  ]
end

to crt-fall-gaps                                                              ;; CREATE FALL GAP PROCEDURE
  ask trees with [fall-gap? = true][                                          ;; The tree fall gap area is calculated from diameter. The radius
    let kill-dist-area (-25.171 + (1.398 * diameter) + (0.02 * diameter ^ 2)) ;; of the sweetspot, which determines sweetspot area, is calculated
    if kill-dist-area < 0 [set kill-dist-area 0]                              ;; from the radius of the fall gap. The gaps are constructed on the
    let kill-dist-radius (sqrt (kill-dist-area / pi))                         ;; landscape by marking the patches within the gap radius as
    let kill-sweet-radius (kill-dist-radius - no-recruit-dist)                ;; disturbance and patches within the sweetspot radius as sweetspot.
    if kill-sweet-radius < 0 [set kill-sweet-radius 0]

    ask patches in-radius (kill-dist-radius / 10) with [disturbance? = false] [set disturbance? true set pcolor red]
    ask patches in-radius (kill-sweet-radius / 10) with [sweetspot? = false] [set sweetspot? true set pcolor red - 2]
  ]
end

to large-disturb
  if large-dist? = true [                                       ;; If the large disturbance option is turned on, this procedure determines
    if random-float 1 < large-dist-prob [                       ;; whether a large disturbance occurs, based on the LARGE-DIST-PROB. If a
      ask one-of patches [                                      ;; large disturbance occurs, it is placed in a random location on the
        let large-dist-radius (sqrt ((large-dist-area * 10000) / pi)) ;; landscape with an area equivalent to the LARGE-DIST-AREA (hectares).
        let large-sweet-radius (large-dist-radius - no-recruit-dist)
        ask patches in-radius (large-dist-radius / 10) with [disturbance? = false] [set disturbance? true set pcolor red]
        ask patches in-radius (large-sweet-radius / 10) with [sweetspot? = false] [set sweetspot? true set pcolor red - 2]
      ]
    ]
  ]
end

;; A tree must have a diameter of 14.85 cm to create a fall gap.
;; A disturbance must be larger than 314.16 m2 to form a sweetspot (dist-radius > 10m , sweet-radius > 0m).
;; A tree must have a diameter of 99.91 cm to create a fall gap large enough (>314.16 m2) to have a sweetspot.
;; A 4 ha large-scale disturbance (default) affects ~2% study area with ~1.6%, or 3.32 ha, in sweetspot (assuming 204ha site).

;; Reproduce Trees Outline
;; ====================================================

to reproduce-trees              ;; REPRODUCTION PROCEDURE
  calc-fruit-prob               ;; This procedure calculates fruiting probability and determines whether a tree fruits.
  disperse-seeds                ;; This procedure determines the number of fruit/seedlings produced by a tree and disperses these seedlings.
end

;; Reproduce Trees Details
;; ====================================================

to calc-fruit-prob                                                              ;; CALCULATES PROBABILITY OF FRUITING
  ask trees with [reproduce? = true][                                           ;; This procedure is only performed by reproductive trees.
```

```
    let fruit-odds (-9.6235667 + (basal-diameter * 0.20970894) -              ;; The probability of fruiting is calculated from the logit
      ((0.18153055) * max (list (0) (basal-diameter - 40))) +                 ;; transformation of "fruit-odds" (log-odds). The CALC-NUM-FRUIT
      (3.2009219 * growth-rate) - ((1.1653679) * growth-rate ^ 2))            ;; function is called for trees that produce fruit.
    set fruit-prob (exp(fruit-odds) / (1 + exp(fruit-odds)))
    if random-float 1 < fruit-prob [calc-num-fruit]
  ]
end

to calc-num-fruit
  let mean-fruit e ^ (0.29582976 + (0.024534028 * basal-diameter) +
                     (0.00033071249 * basal-diameter ^ 2) - (1.7436957 * 10 ^ -6 * basal-diameter ^ 3))

  let alpha 1.141525                                           ;; CALCULATES NUMBER OF FRUIT
  let lambda (alpha / mean-fruit)                              ;; This function calculates the number of fruit from a gamma distribution
  set num-fruit random-gamma alpha lambda                      ;; parameterized by alpha and lambda values. The number of fruit is multiplied
  if num-fruit > max-num-fruit [set num-fruit max-num-fruit]   ;; by the seeds per fruit constant to determine the number of seeds produced.
  let num-seeds num-fruit * seeds-per-fruit                    ;; This number is reduced by the seed-seedling survival probability to determine
  set seedlings floor (num-seeds * establishment-rate)         ;; the total number of surviving seedlings.
end

to disperse-seeds                                                        ;; DISPERSES SEEDLINGS
  let seed-radius sqrt (seed-shadow-area * 10000 / pi) / 10              ;; This function disperses seedlings uniformly in the seed shadow
  ask trees with [seedlings > 0][                                        ;; of the parent tree. It disperses seeds by selecting a random
    hatch seedlings [                                                    ;; direction from the uniform distribution from 0 to 360 degrees
      set heading random 360                                             ;; and a random distance using the standard method for uniformly
      let dispersal-distance seed-radius * sqrt(random-float 1)          ;; picking a random point within a circle. Successful recruitment
      forward dispersal-distance                                         ;; requires sweetspot; only seedlings landing in sweetspot survive.
      ifelse [sweetspot?] of patch-here = true [
        set basal-diameter one-of seed-diam-data                         ;; Basal diameter (cm) is drawn from the seedling diameter list.
        set diameter calc-diam basal-diameter                            ;; Diameter (cm) is calculated from the basal diameter.
        set basal-area calc-basal-area diameter                          ;; Basal area (m2) is calculated from diameter.
        set stand-volume calc-stand-volume diameter                      ;; Standing volume (m3) is calculated from diameter.
        set sawn-volume calc-sawn-volume diameter                        ;; Sawn volume (m3) is calculated from diameter.
        set size 1 + diameter / 50                                       ;; Trees are sized based on diameter.
        set shape "tree"                                                 ;; Trees are shaped as "trees".
        set color green - 3                                              ;; Trees are colored green.
        set age 1                                                        ;; All seedlings are 0 years old.
        set alive? true                                                  ;; All seedlings are alive.
        set seedling? true                                               ;; All seedlings are seedlings.
        set fall-gap? false                                              ;; No initial trees create fall gaps (still alive).
        set reproduce? false                                             ;; No seedlings are reproductive.
        set growth-rate one-of seed-growth-data                          ;; Growth rate (cm/yr) is drawn from the seedling growth rate list.
        set mort-prob 0                                                  ;; Mortality rate initially 0 because it is set later.
        set fruit-prob 0                                                 ;; Fruiting probability initially 0 because it is set later.
        set num-fruit 0                                                  ;; Number of fruit initially 0 because it is set later.
        set seedlings 0                                                  ;; Surviving seeds initially 0 because it is set later.
        set e10 growth-rate - mean seed-growth-data                      ;; Tenth-year residual is randomly selected.
        set e9 0                                                         ;; Ninth-year residual is zero.
        set e8 0                                                         ;; Eighth-year residual is zero.
        set e7 0                                                         ;; Seventh-year residual is zero.
        set e6 0                                                         ;; Sixth-year residual is zero.
        set e5 0                                                         ;; Fifth-year residual is zero.
        set e4 0                                                         ;; Fourth-year residual is zero.
        set e3 0                                                         ;; Third-year residual is zero.
        set e2 0                                                         ;; Second-year residual is zero.
        set e1 0                                                         ;; First-year residual is zero.
        set e0 calc-e0 e1 e2 e3 e4 e5 e6 e7 e8 e9 e10                    ;; Present-year residual is calculated from e1-e10.
      ][
        die
```

```
      ]
    ]
  ]
end

;; Remove Trees and Disturbances
;; ==================================================

to remove-trees                                                   ;; REMOVE DEAD TREES
  ask trees with [alive? = false][die]                            ;; Dead trees are removed from the population.
end

to remove-gaps                                                                     ;; REMOVE DISTRURBANCES
  ask patches with [disturbance?][set disturbance? false set pcolor green]        ;; Disturbances are removed from the landscape annually.
  ask patches with [sweetspot?][set sweetspot? false set pcolor green]            ;; Neither disturbances nor sweetspot last more than a year.
end

to reset-trees                              ;; TREE VARIABLES RESET
  ask trees [                               ;; These variables are reset at the end of each time step in preparation for the next time step.
    set seedling? false                     ;; These values are not recalculated every year so retaining them through a non-reproductive
    set fall-gap? false                     ;; would inflate population outcomes. The recalculation of these values in other years is independent
    set reproduce? true                     ;; of the values in previous years so it's okay to annually reset them.
    set fruit-prob 0
    set num-fruit 0
    set seedlings 0
  ]
end

;; EXPORT RESULTS
;; ====================================================================================================

to export-results
  user-message "Please include the '.txt' extension in the data file name."
  file-open user-new-file

  ;; MODEL PARAMETERS / GENERAL STATISTICS
  ;; ======================================

  let log-text "" let pop-text ""
  ifelse Logging [set log-text "ON"][set log-text "OFF"]
  ifelse member? "User" Populations [set pop-text File-Name][set pop-text Populations]

  file-print "SIMULATION RESULTS"
  file-print (word ("Site Name: ") (pop-text) ("; Site Area: ") (precision (site-area) 1) (" ha"))
  file-print (word ("Logging: ") (log-text) ("; Number of Harvest Cycles: ") (floor (ticks / cutting-cycle) + 1) (" cycles"))
  file-print (word ("Time Limit: ") (Time) (" years; ") ("Time Reached: ") (ticks) (" years"))
  file-print ""

  ;; GENERAL INFORMATION
  ;; ======================================

  file-print (word "The following summary represents the results of a single simulation. To validate these results, please conduct"
    " more simulations. You can do this by running single-run simulations (repeats of the current simulation) or by running a"
    " BehaviorSpace experiment. Please see the User Manual for more information.")
  file-print ""

  file-print (word ("* 'Total Abundance/Density' statistics pertain to trees larger than ") (small-diam) (" cm diameter. 'Commercial Abundance/")
    ("Density' statistics pertain to trees larger than the commercial diameter (") (minimum-diameter) (" cm)."))
  file-print ""
```

```
;; LOGGING PARAMETERS
;; ======================================

ifelse Logging = true [
  file-print "LOGGING PARAMETERS"
  file-print (word ("Minimum Diameter:        ") (minimum-diameter) (" cm"))
  file-print (word ("Retention Rate:          ") (retention-rate) (" % commercial trees"))
  file-print (word ("Minimum Density:         ") (minimum-density) (" commercial trees / 100 ha"))
  file-print (word ("Cutting Cycle:           ") (cutting-cycle) (" years"))
  file-print ""
][
  file-print "THE LOGGING FUNCTION WAS NOT TURNED ON. NO TREES WERE LOGGED DURING THIS SIMULATION."
  file-print ""
]

;; POPULATION STATISTICS
;; ======================================

file-print "YEAR O STATISTICS"
file-print (word ("Total Abundance:         ") (floor (y0-tree-density * site-area / 100)) (".0 trees"))
file-print (word ("Total Density:           ") (precision y0-tree-density 1) (" trees / 100 ha"))
file-print (word ("Commercial Abundance:    ") (floor (y0-comm-density * site-area / 100)) (".0 trees"))
file-print (word ("Commercial Density:      ") (precision y0-comm-density 1) (" trees / 100 ha"))
file-print (word ("Commercial Volume:       ") (precision y0-comm-volume 1) (" m3"))
file-print ""

file-print (word ("YEAR ") (ticks) (" STATISTICS"))
file-print (word ("Total Abundance:         ") (count trees with [diameter >= small-diam]) (".0 trees"))
file-print (word ("Total Density:           ") (precision (count trees with [diameter >= small-diam] / site-area * 100) 1) (" trees / 100 ha"))
file-print (word ("Commercial Abundance:    ") (count trees with [diameter >= minimum-diameter]) (".0 trees"))
file-print (word ("Commercial Density:      ") (precision (count trees with [diameter >= minimum-diameter] / site-area * 100) 1) (" trees / 100 ha"))
file-print (word ("Commercial Volume:       ") (precision (sum [stand-volume] of trees with [diameter >= minimum-diameter]) 1) (" m3"))
file-print ""

;; HARVEST STATISTICS
;; ======================================

if Logging = true [
  file-print "HARVEST STATISTICS"
  file-print (word ("Number of Harvests:      ") (floor (ticks / cutting-cycle) + 1) (" cycles"))
  file-print (word ("Number of Logged Trees:  ") (precision length tot-logged-volume 1) (" trees"))
  file-print (word ("Volume of Logged Trees:  ") (precision sum tot-logged-volume 1) (" m3"))
  file-print ""
]

if Logging = true and ticks > 1 [
  let cycle n-values length annual-harvest-number [? + 1]
  (foreach cycle annual-harvest-number annual-harvest-volume [
    file-type (word "Harvest " ?1 " (Year " ((?1 - 1) * cutting-cycle + 1) ")")
    file-type (word ": " ?2 " trees")
    file-print (word "; " ?3 " m3")
  ])
  file-print ""
]

;; PRE/POST HARVEST ABUNDANCE & VOLUME
;; ======================================
```

```
  if Logging = true and ticks > 1 [
    file-print "PRE/POST HARVEST ABUNDANCE & VOLUME"

    let harvest-cycle n-values (length pre-post-cut-number / 2) [? + 1]
    let pre-cut-number n-values (length pre-post-cut-number / 2) [item (? * 2) pre-post-cut-number]
    let post-cut-number n-values (length pre-post-cut-number / 2) [item (? * 2 + 1) pre-post-cut-number]
    let pre-cut-volume n-values (length pre-post-cut-volume / 2) [item (? * 2) pre-post-cut-volume]
    let post-cut-volume n-values (length pre-post-cut-volume / 2) [item (? * 2 + 1) pre-post-cut-volume]

    (foreach harvest-cycle pre-cut-number post-cut-number pre-cut-volume post-cut-volume [
      file-print (word "Harvest " ?1 " (Pre-Harvest): " ?2 " trees; " ?4 " m3")
      file-print (word "Harvest " ?1 " (Post-Harvest): " (?3) " trees; " (?5) " m3")
      file-print ""
    ])

    file-print (word ("* These statistics describe the standing commercial population before/after harvest using the logging ")
      ("parameters above."))
    file-print ""
  ]

  ;; END YEAR SIZE DISTRIBUTION
  ;; ======================================

  file-print (word ("SIZE DISTRIBUTION (YEAR ") (ticks) (")"))
  let min-bin 20
  let bin-size 10
  let max-diam max [diameter] of trees
  let max-bin ceiling (max-diam / bin-size) * bin-size
  let diam-bins n-values ((max-bin - min-bin) / bin-size + 1) [min-bin + bin-size * ?]
  foreach diam-bins [
    file-print (word (?) (" - ") (? + bin-size) (" m3:               ")
    (count trees with [diameter >= ? and diameter < (? + bin-size)]) (" trees"))
  ]
  file-close
end

;; END PROGRAM
;; ==========================================================================================
```