

ShadeMotion 2.2:

Simulation of tree shades in horizontal or tilted plots

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1. Preface

In the early years of agroforestry at CATIE, in the 1980s, we agroforestry researchers debated over the applicability of systematic experimental plantation in agroforestry research. Arguments against these designs sought to prove that specific planting densities shown on the planting map (in a systematic design, the planting density is constantly –systematically– changing along one or two gradients on the land) had little validity in an agroforestry system wherein the plants comprising it vary greatly in overall size or height.

For example, the coffee plantations in Turrialba contain: 1) Spanish elm trees –*Cordia alliodora* (*laurel* in Spanish) – a timber-yielding species reaching overall heights of roughly 82 ft.; 2) trees specifically for shade, in this case mountain immortelle –*Erythrina poeppigiana*– (*poró* in Spanish) removing the crown twice per year, which does not exceed an overall height of 13 ft; and 3) coffee trees –*Coffea arabica* cv. *Caturra*– which barely attain heights of 6½ ft. Due to these plant height differences, each coffee tree is influenced by a neighborhood that includes two effects: 1) the one indicated by the planting position of mountain immortelle, Spanish elm and other neighboring coffee plants, and 2) the one created by the shade cast by the mountain immortelle and Spanish elm trees located within the neighborhood of each coffee tree. A simulation tool was needed that could allow us to determine the amount of shade reaching each coffee tree plantation site which had a systematic spacing design, that is, we needed a tool that would allow us to determine the “neighborhood” of trees providing shade to each point in the plantation design.



CATIE agroforestry researcher Eduardo Somarriba, mathematician Francisco Quesada, and computer engineer and programmer Eduardo Vargas, joined forces to develop a computer program to model tree shadow patterns in agroforestry systems planted on flat and sloping lands. This working team met over several months and created a shade simulator, the main purpose (kept unchanged to date) of which is consistent with the original idea: calculate cumulative hours of shade at all “points” in the land area, during a certain given time period, given the presence of trees on the plot of land.

The shade pattern simulation program was developed in Basic computer language for the DOS environment, the operating system used by personal computers at the time (led by the imposing AT, with its flamboyant 386 microprocessor and a large 20 MB hard drive!). The 1987 version of this software package had no graphical interface whatsoever, its results were saved in a text file and a modest-sized simulation routinely took several hours to produce (Quesada et al, 1987). Despite these limitations, the program was used by several agroforestry researchers at CATIE and in Brazil, and it proved useful to several graduate students conducting research as part of their master’s degree programs. Later on, it completely vanished into obscurity.

A decision was made in 2008 to resurrect and redesign the shadow simulator to capitalize on the swift, new, early 21st century personal computers, new programming languages, multimedia platforms and the graphical interfaces that are so ubiquitous nowadays. The new simulator was christened “ShadeMotion” and redesigned around a user-friendly, graphical interface that can be accessed on the Web. The old mathematical algorithms were improved and extended, adding



new functions to serve the needs of users. ShadeMotion was developed in the .Net programming environment, in C# computer language, with programming led by computer science engineer Matthias Malek. Development of ShadeMotion is ongoing. The authors are currently working on a module that integrates ShadeMotion with ArcGis --a powerful geographical information systems (GIS) software, so that you may enter data and run simulations from ArcGis. By the time this manual is printed, the mentioned update would quite possibly be available on the website: www.shademotion.com.

The aim of this manual is to teach the reader how to build simulations quickly using ShadeMotion. In general, the content of this manual is as follows: after presenting the program's work environment, the reader is introduced to the use of ShadeMotion with a few model examples of simple simulations. The following sections and examples are devoted to presenting ShadeMotion's further capabilities; for example, how to factor in crown density and monthly variation in foliage over a year's time and to create models on inclined land areas and how to expedite the input of data into the program, and so on. A concise description of how ShadeMotion works and the mathematical algorithms used in shade calculations appears at the end of the manual.

The analysis and modeling of plant crowns and transmission of solar radiation through plant crowns have been the subjects of study and technological development in several disciplines. For example, in architecture and landscaping, a great deal of software aimed at using the computer to recreate the way that the effects of light and shade is perceived by humans on surfaces with varying degrees of smoothness has been developed for use in virtual reality programs, computer



games, and three-dimensional design (such as AutoCad, SketchUp or Blender, among others). Other programs attempt to measure the effect wielded by light and shade cast by buildings or screens of trees on the temperature of indoor environments, for applications in architecture or air conditioning system installations. Models have been designed in the fields of ecology, agriculture, and environmental sciences to study the three-dimensional shape and location of the crown in the forest or in an agroforestry system, and their effects on the capture of solar radiation. Some models reconstruct precise three-dimensional copies of trees and crops and make it possible to calculate photosynthesis, and the development, growth, and production of plants.

ShadeMotion is a simple tool for preliminary visual on-screen exploration of the shade patterns produced by planting trees in any spatial arrangement on the ground. Despite its outward simplicity, ShadeMotion creates files with detailed information about the shade cast over each point on the land. These files allow you to conduct spatial analyses and analyses of more profound interactions. We expect that ShadeMotion users will find the program easy to use and helpful for designing agroforestry systems worldwide.



2. Introduction

What is ShadeMotion?

ShadeMotion is a software that calculates the position and shape of shades projected onto the ground by the crowns of trees planted on flat, horizontal or tilted plots in any location on Earth and at different dates and times. This software is available at the Web site: www.shademotion.com. Its main purpose is to answer questions such as:

How many hours of shade are accumulated in each “point” of a plot where trees are planted, during a certain period of time?

ShadeMotion is a very easy-to-use software and allows users to choose from a wide range of options when constructing simulations. Version 2.2 of this program also enables users to “map” shade on tilted planes. To build a simulation you can choose from the following options:

- Number of trees on the plot
- Location of each tree on the plot
- The shape of each tree crown (selected from a limited number of options)
- Size of the crown and height of the trunk of each tree
- Density of each crown
- Monthly foliage variations for each crown



- Various options for determining plot size
- Starting and ending dates of the simulation and daily hour range for the calculation of shades
- Measurement units for the trees and the plot
- Frequency of solar movement (how often the position of the sun and the shades is recalculated)
- The height above ground level at which we wish to determine the distribution of shades
- Geographic latitude where the plot is located
- Maximum slope or angle of inclination of the plot
- Orientation of the slope with respect to the North

How the simulation results are presented

Once the user has entered the input data about the plot and trees on it, and has instructed ShadeMotion to process this information, the program shows the results both graphically and numerically.

In the first case, ShadeMotion builds a visual pattern of the shade in different tonalities of grey on a grid representing the plot. The darker tones indicate the cells or areas with the highest accumulation of shade units. The program also saves the total hours of shade accumulated in each cell of the grid during the simulation period. The results can be viewed by simply placing the pointer of the mouse on the desired cell. All the simulation data can be saved in a file for further analysis and can also be exported to Excel files.



3. The ShadeMotion screen

If you have already opened the ShadeMotion program, you will see the Main window on your screen showing a grid that represents the plot where trees are planted.

Main Window

The Main window comprises five elements:

1) Title Bar, 2) Menu Bar, 3) Tool Bar, 4) Grid Area and 5) Status Bar, as shown in Figure 1.

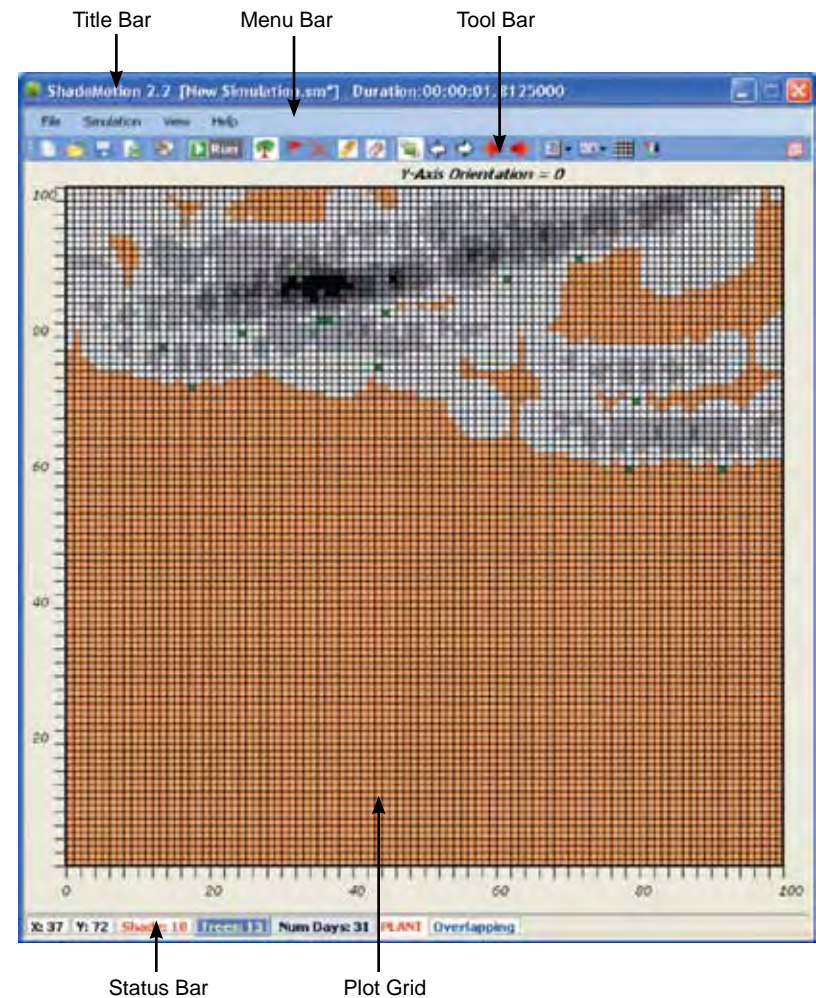


Figure 1. Features of the Main window



Title Bar

This shows the name and version of the program and includes the usual Windows application buttons to close or minimize the ShadeMotion screen.

Menu Bar

There are four Windows-style drop-down menu options: File, Simulation, View and Help, each with its own options.

Tool Bar

Figure 2 shows the 21 icons of the Tool Bar. A more detailed explanation of their use is provided in the examples below.

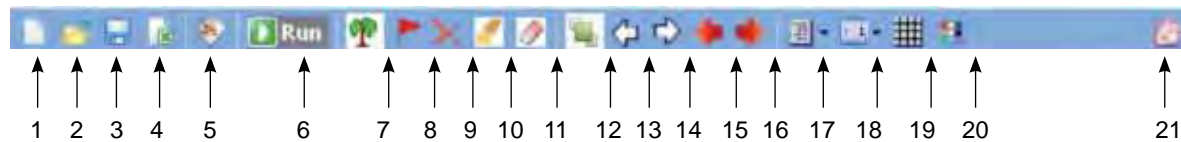


Figure 2. Tool Bar Icons

Tool Bar Icons

1. Starts a new simulation
2. Opens a simulation from a file
3. Saves the simulation in a ShadeMotion file



4. Exports simulation data to two Excel files
5. Opens the Simulation Properties Window
6. Runs the simulation
7. Activates planting trees capacity
8. Activates placing flags capacity
9. Activates capacity for erasing trees or flags individually
10. Removes all trees, flags and shades from the plot
11. Removes only shades from the plot, leaving trees and flags
12. Alternates between the “With Overlaps” and “Without Overlaps” status
13. Moves shades one time-unit backward
14. Moves shades one time-unit forward
15. Moves shades to previous time-unit, without erasing previous shades
16. Moves shades to the next time-unit, without erasing previous shades
17. Selects one of three shading styles
18. Selects one of three plot sizes
19. Shows/hides grid lines
20. Changes the colors of the plot, trees and flags
21. Opens the ShadeMotion tutorial (pdf format)

Plot Grid

The orange grid represents the square plot where trees are planted. By default, each side of the plot measures 100 units of length (abbreviated to u.l.). Users may also select plots measuring 50 u.l. and



200 u.l. Users may interpret these units of length as they wish, provided that the tree measurements are also entered in these same units. All the examples included in this guide use meters as units of length and work with a plot measuring 100x100 meters, corresponding to an area of 10,000 square meters (one hectare), where each cell represents one square meter.

Each cell in the grid is identified by its central point, using a pair of numbers or Cartesian coordinates, as is usual in analytical geometry. The origin of coordinates is located in the lower left-hand corner of the grid, with the X axis running horizontally along the base of the plot and the Y axis running vertically along the left side of the plot. By default, the positive Y axis points North, although this changes when the plot is on a slope, as is explained further on. We suggest that you place the mouse on any cell in the grid and, without clicking, notice how its coordinates appear on the Status Bar. Now, gently move the pointer over the grid and see how the coordinates of the cells gradually change as it moves across the cells.

Status Bar

This displays the number of trees planted on the plot, the number of days in the simulation period and the amount of shade received by any cell under the mouse pointer. When simulating the shade cast by one or several trees at a given time of the day, the Status Bar also shows the elevation and azimuth angles of the sun (Example 1).



4. Building basic simulations

This section introduces the basic operations for constructing simulations, using two examples.

Example 1: Shade projected by the crown of a tree at a given “moment” and during one day

In this example we will plant one tree near the center of the plot and will examine the shade projected by the tree at noon, on a particular day of the year. First, click on the little green tree icon in the Tool Bar to activate the Planting status of ShadeMotion. When the program is in this mode, the sign “Planting” appears in the Status Bar. Next, move the mouse pointer to a cell somewhere near the center of the plot where we will plant our tree and left-click on the mouse. The Tree Properties window will open (Figure 3) for you to enter the characteristics of the tree that you will plant: crown shape, crown height and width and height of the trunk (distance from the ground to the base of the crown). In this first example we will not change any of the values given in the window (default values).

To plant the tree, click on the OK button. The window will immediately close and the cell where the tree was planted will turn green, the color assigned by default to ellipsoidal crowns.



Figure 3. Tree Properties window in example 1.



Now open the Simulation Properties' window and click on the Properties Simulation icon on the Tool Bar (Figure 4).



Figure 4. Simulation Properties Icon on the Tool Bar

In this window, we enter the global data of the simulation: starting and ending date and time, geographic latitude, time unit (how often the sun's position is recalculated) and other parameters, which will be explained as we go along. Although none of the settings in this window are changed in this example, we ask you to open it and look at the values of the remaining parameters in this example. The Properties Simulation Window (Figure 5) shows the starting and ending date as January 1, 2010, the starting and ending time as 12 noon and the latitude as 0° . In other words, the tree has been planted on the Equator. These are the default values shown in the window each time the program initiates.

When the starting and ending dates coincide, as well as the starting and ending times, this means the program will generate the shade corresponding to "a moment" of time (and not to a period of time between two moments).

To run the simulation, move the mouse to the Tool Bar and click on the Run Simulation icon. A grey spot will immediately appear on the plot representing the shade. Notice that the Status Bar shows



the angle of elevation and the azimuth of the sun at that “moment” and at that latitude. If you are not familiar with the meaning of these angles, this point is explained further on (Section 10).

Continuing with the example, we will now see how a shade changes its position and shape in the course of a day. Locate the two white arrow icons in the Tool Bar, which are shown in Figure 6:

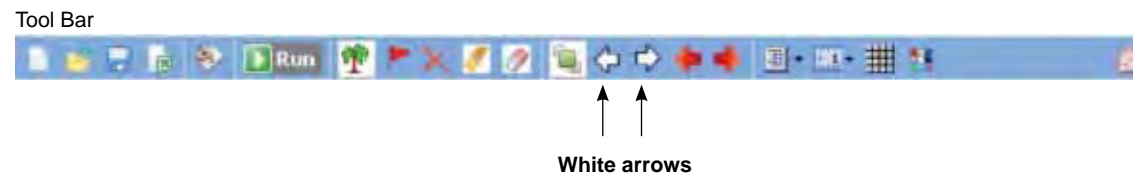


Figure 6. White arrows icon on Tool Bar

The arrow pointing to the right is used to increase the time by one time-unit while the arrow pointing to the left is used to decrease it. By default, the time-unit is set at 1 hour, but the user can change it at will (we suggest you leave it unchanged for the moment). Click once on the right arrow and notice how the shade moves to a new position to the right. Now click several times on the right arrow until the shade eventually disappears from the plot to the right (towards the East), because the sun is moving left (towards the West). Next, click on the left arrow and see how the shade reappears on the plot, because you are decreasing the time. Move the shade backward in time until it is 8 a.m. The time and the sun’s position are updated in the Status Bar each time you move the shade. Now, use the red arrows located to the right of the white arrows. Click on the red arrow pointing



Figure 5. Simulation Properties Window in example 1

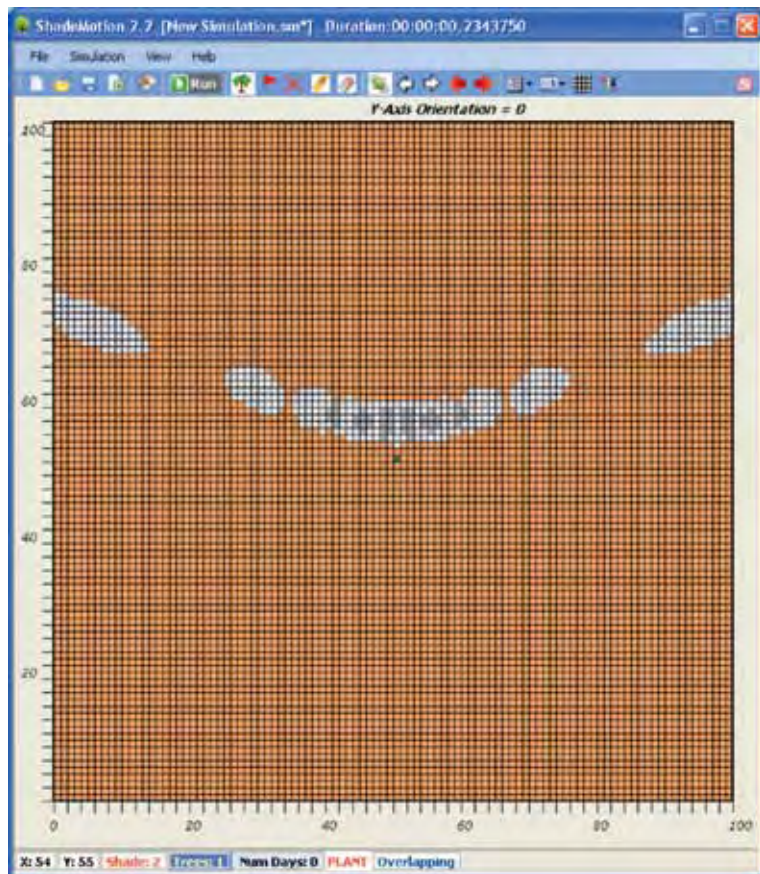


Figure 7. It shows the path of the shade cast by a tree between 7 a.m. and 5 p.m. on January 1st, at latitude 0, calculated at hourly intervals. The Status Bar shows that the cell (54, 55) received two hours of shade (Note: the mouse pointer has been placed over this cell, but this is not visible in the illustration).

to the right. Notice how the shade changes position but this time the traces of the previous shades remain on the plot. This option allows you to visualize the path of the shade in the course of the day. By changing the date or the latitude, you can also compare the paths of the shade for different times of the year or for different geographic latitudes. The white and red arrows can only be used when the initial date and time coincide with the final date and time.

We will complete this example by clearing the trees and shades from the plot. Find the Clear Plot icon on the Tool Bar, which looks like an eraser with a yellow tip (Figure 8).



Removes all trees and all shades. Removes all shades but not the trees.

Figure 8. Icon to remove trees and shades on the Tool Bar

Click on this icon. A warning window will open asking you to confirm this action. Confirm the action to clear the plot. The eraser icon with the white tip is used to remove shades but



without removing trees on the plot (Figure 8). This eraser is useful when you wish to re-run the simulation, introducing changes in some parameters but without having to plant the trees all over again.

Example 2: Shade accumulated over a period of several days

This example shows you how to determine the number of hours of shade received by each cell on the plot over a period of several days. The steps are as follows:

1. Enter new values in the Tree Properties window and plant four trees with identical characteristics
2. Use the right button of the mouse or the <Enter> key to plant identical trees
3. Define the starting and ending dates of the simulation
4. Define the daily hour range of the simulation
5. Run the simulation

Begin by clicking on the little tree icon to ensure that the program is in Planting mode. Then move the mouse pointer to the cell with coordinates (20, 60) and left-click to open the Tree Properties window. Now enter the following new values:

Crown shape = Ellipsoidal

Crown width = 8

Crown height = 10

Trunk height = 12



Figure 9. Tree Properties window in example 2.



Let us assume that all the measurements are in meters. You can move from one field to the next by using either the pointer or the <TAB> key. The use of the Crown Density and Foliage Variation buttons that appear in the window is explained in Section 6. For now we will not modify any of these values. Click on the <OK> button to plant the first tree. The following three trees will have these same values. ShadeMotion stores the values of the last tree that was planted in its memory—helping you to save time when you wish to plant trees with identical characteristics.

All you need to do now to plant the remaining three trees is **take the pointer to the cell where you wish to plant the next tree and right-click on the mouse or press <Enter>**. To plant three more identical trees simply move the pointer to the cells (40, 60), (60, 60) and (80, 60).

Next we will change some of the global parameters of the simulation: latitude, dates and daily hour range of the sun's movement. Enter this data in the Properties Simulation window. This can be opened by clicking on the Properties Simulation icon of the Tool Bar (Figure 10).



Figure 10. Simulation Properties window in Example 2.

Enter the following values:

Starting date = 06/01/2010 (June 1, 2010)

Ending date= 07/01/2010 (July 1, 2010)

Starting time= 7 (7 a.m.)

Ending time = 17 (5 p.m.)

Latitude = 10 (10° North)



To change the starting date or time click on the appropriate field and type in the number; you can also use the vertical movement arrows of the cursor to increase or decrease these values. A calendar may also be opened to change the starting or ending date by clicking on the “v”-shaped blue buttons, located on the right. The value 0° latitude corresponds to the Equator. In the northern hemisphere, the latitude is entered with positive values and in the southern hemisphere with negative values. To enter fractional latitude values, the minutes and seconds must be previously converted to decimals.

In this example we suggest that you do not change the other parameter values. Their meanings will be explained in Sections 6 and 7. Please note that the starting time and ending time are applied to each day of the simulation period. In other words, in this example the program will calculate the shades between 7 a.m.– 5 p.m., at one-hour intervals, for each day between June 1 and July 1, 2010 (i.e. for 30 days). ShadeMotion will produce a shade pattern like the one shown in Figure 11.

Place the pointer on one of the cells in the shaded area; the Status Bar will show the coordinates and the number of hours of shade accumulated in that cell.

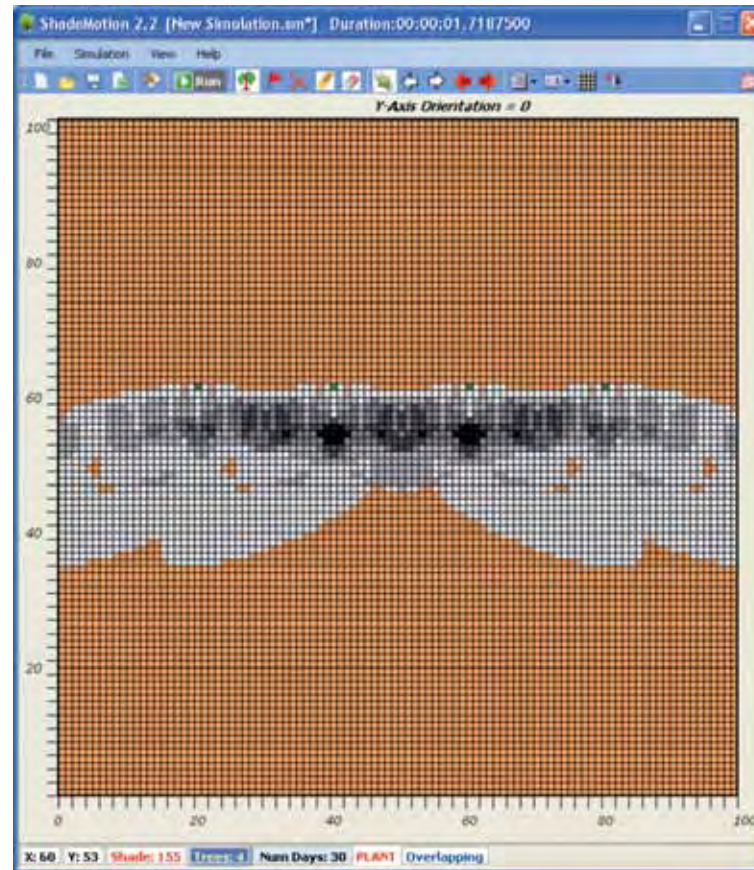


Figure 11. The various grey tones indicate the number of hours of shade accumulated on each cell during the simulation period.



5. Some important operations

Before showing you how to use other options of the ShadeMotion program, which expand the range of plots that can be simulated, we will try to anticipate and answer some questions that the reader may have. We will also take advantage of this section to introduce a faster way of planting or erasing trees, using the keyboard.

How to erase trees and shades from the plot

At the end of Example 1, we saw how to remove all the trees and their shades from the plot or how to erase only the shades. However, there may be times when the user does not wish to erase all the trees on the plot, but only some of them. There are two ways of doing this:

- 1. First method:** Take the mouse pointer to a cell where a tree has been planted and left-click on it. When the Tree Properties window opens you will notice that the Remove button is now active. Click on this button to remove the tree.
- 2. Second method:** Click on the red “X” icon located to the left of the two erasers. This will change the program’s status from Planting to Erase. Next, take the pointer to the cell containing a tree that you wish to remove and press either of the two mouse buttons, or else press <Enter>. Repeat this action with the other trees that you wish to remove. Remember that ShadeMotion is now in the Erase status and will remain so until you instruct it otherwise. If you wish to plant more trees you must activate the Planting status once again.



Using the keyboard to plant and erase trees

Using the mouse to locate pre-determined coordinates in the plot can be somewhat difficult, given the small size of the cells, especially when using a 200 x 200 grid. For this reason, the program offers an alternative way to locate cells using the four arrow keys (cursor) on the keyboard. Begin to experiment by pressing on the arrows of the cursor. You will notice that these move a yellow cell over the grid, which we will call the **yellow point**. The yellow point will always begin its movement from the cell nearest to the mouse pointer. It can be moved over the grid in the four directions shown by the arrows: up, down, right and left. When ShadeMotion is in the Planting status, you can plant a tree taking the yellow point to the desired cell and pressing <Enter>. The following table explains how to use this modality to plant, remove or change the tree parameters.



Table 1. Using the four arrow keys (cursor) keys to plant trees

Desired effect	Action
To locate a cell	Place the mouse pointer near the place where you wish to plant a tree. Keeping the mouse still, use the four arrow keys to move the yellow point to the desired cell.
To plant or erase a tree	Previously activate the desired status (Planting or Erase), move the yellow point to the desired cell and press <Enter>
To open the Properties Tree window and check or change the tree parameters	Take the yellow point to the desired cell and simultaneously press the <Control> and <Enter> keys.

How to save a simulation

Saving a simulation means storing all the data in a file, so that the simulation can be reproduced at a future time. ShadeMotion saves the simulations in the program's own format. All the data entered by the user, as well as the status of the screen, are saved under this format. The first time you save a simulation use the **save as** option of the File Menu. At this point you must give the simulation a file name. If you do not do so, ShadeMotion will assign it a generic name (for example, Simulation 1 or Simulation 2). ShadeMotion files are saved with the extension ".sm". If you do not add this extension, the program will do it automatically. Any subsequent changes made in the simulation must be updated using the **save option** of the **File** Menu. ShadeMotion simulations can also be exported as Excel files (extension .xls), an aspect that is discussed further on.



Warning

When using the four arrow keys keep the mouse as still as possible. The slightest accidental movement of the mouse will cause the yellow point to jump back to the cell nearest the pointer, as if attracted by a magnet, and you will have to start all over again.



6. Fine-tuning details and expanding the repertoire of possible simulations

This section describes other options offered by ShadeMotion to expand the repertoire of possible simulations. Let us begin by introducing two parameters that model the amount of light penetrating the crown of a tree, depending on how closed (dense) or open (sparse) the foliage is, and on its monthly rates of leaf-fall and leaf growth.

Crown density

The first parameter is termed **crown density** and enables us to compare the foliage on the crowns of different tree species. Given that a tree's foliage tends to vary during the months of the year, the crown density must be estimated for a time of year when the foliage is at its maximum. For example, a tree with an 80% crown density is one that in its state of maximum foliage produces a shade comprising 80% "dark zone" and 20% "light flecks". The program introduces the light flecks at random and recalculates these each time that the sun changes its position, without taking into account of their previous location. To assign a value to a tree's crown density, adjust this parameter using the Crown Density slider located in the Tree Properties window and pressing the button <OK> so that the change has some effect.



Example 3. Crown density

Open the Properties Simulation window and enter the starting and ending dates and times of the same value to generate shade at a single moment of the day. Plant two identical trees, assigning a crown density of 100% (default value) to the first and a crown density of 60% to the second. When you run the program you will see a difference similar to the one shown in Figure 12.

Question: After running a simulation for a single tree with a 50% crown density, for a period of 6 months, we do not see light flecks in the shade pattern. Why?

Answer: Because the shade is in movement and the light flecks are generated at random; a fleck generated at a certain moment may be covered by the shade of the crown at a later time. The probability that the flecks will be covered by subsequent shades increases as the simulation period increases. However, the effects of the light flecks continue to be present and are reflected in the accumulated shade totals in each cell. You can confirm this fact by running another simulation and changing the crown density to 100%. If you compare the accumulated totals in cells

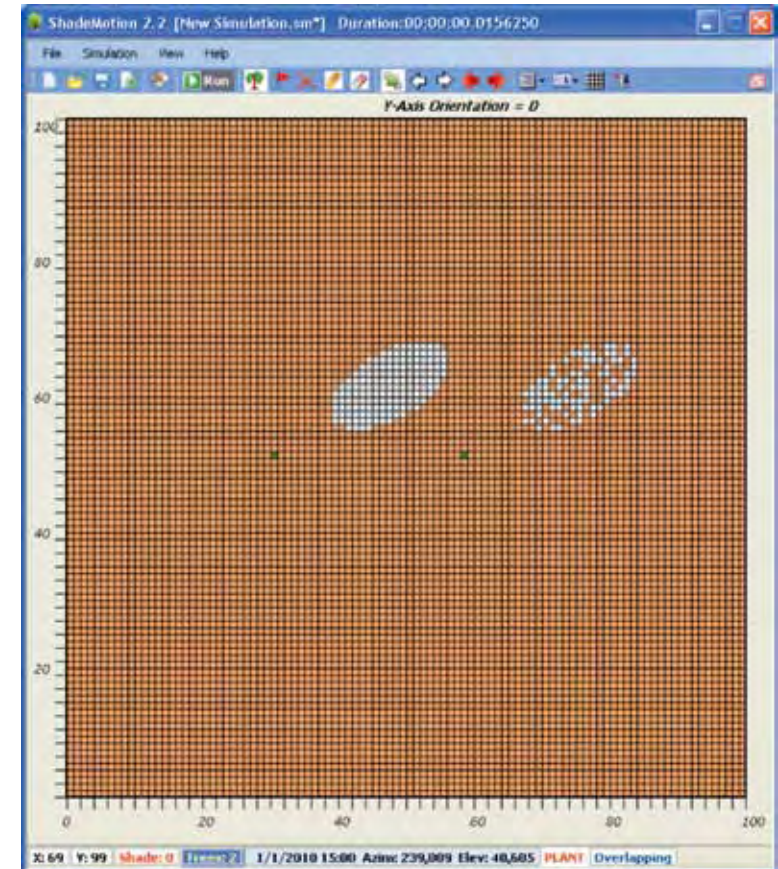


Figure 12. Shades cast by two trees with crowns of identical shape and size, projecting their shades on the same day and at the same time. Their crown densities are 100% and 60% respectively. Within the shade contour on the right, ShadeMotion has randomly generated 40% "light flecks".



with the same coordinates for both simulations, you will see that in the first case the totals accumulated are less than in the second case.

Monthly foliage variations

ShadeMotion also allows us to model the monthly foliage variations observed in trees during their annual cycle—a phenomenon known as caducifolia. Monthly foliage variations are determined in the Tree Properties window. If you click on the Foliage Variation button a panel will appear with twelve sliders, similar to those found on a sound mixer. Each slider may be moved between the values 0 and 100. A value of 100 is assigned to those months of the year when a tree's foliage reaches its maximum. When simulating a tree in which the foliage varies during the year, the user should place the sliders in a position that matches each month's variations—as though they were points of a curve describing the increase and decrease of the foliage, as shown in Figure 13.



Figure 13. It shows the position of the sliders for a tree species that begins the year with 51% of its foliage, reaches its maximum foliage (100%) between May and August and then gradually experiences a decrease in foliage until it again reaches 51% at the end of the year.

Crown opaqueness in a given month

The **opaqueness** of a tree's crown in a given month corresponds to the percentage of dark area present in the shade projected by that crown during that month. Crown opaqueness during a month results from the combined effect of the crown density and the percentage of foliage for that month and is obtained by multiplying both percentages. To better explain this concept, let us assume that we have a tree whose monthly foliage variation is represented by the panel in Figure 13. Let us suppose that the tree has a crown density of 50% and that we wish to calculate the crown's opaqueness in the month of January. Given that the slider for January shows a value of 51%, the opaqueness or percentage of dark area in its shade will be equivalent to 51% of 50%, in other words $0.51 \times 0.5 \times 100 = 25.5\%$.



The meaning of shades overlapping

ShadeMotion makes two separate calculations for the total hours of shade accumulated in each cell of the grid. The first calculation takes into account the overlapping of shades cast by different trees on the same cell at the same time, whereas the second calculation does not. To explain the difference between both these cases, let us suppose that on a certain day of the simulation period, at 9 a.m., the program detects that three trees are projecting shade onto a particular cell. The question is: should the program add 1 unit of shade (without overlaps) or 3 units of shade (with overlaps) to the total already accumulated in that cell at that moment? To make life easier for the user, ShadeMotion calculates both possibilities. The preference for one or the other option depends on the user's objectives. When working with crowns that are not 100% opaque—where there are light flecks—it seems reasonable to take account of the overlaps, since the light flecks on a crown at a given moment may be covered by the shade of another crown at that same moment. By default, ShadeMotion counts the overlaps in the totals. The results without the overlaps may be seen by pressing the Overlap Shades icon on the Tool Bar (Figure 14).



“With Overlaps” and “Without Overlaps”

Figure 14. Icon to switch between the “With Overlaps” and “Without Overlaps” status in the Tool Bar.



If you press this button again you return to the With Overlaps option. The current option is shown in the Status Bar, which displays the sign With Overlaps or Without Overlaps. A quicker way to compare the values for both options in a given cell - without having to move the pointer of the cell and lose your place- is to simultaneously press the keys <CTRL>and <T>. The effect of this combination is to alternate between the With Overlaps and Without Overlaps options.

Placing flags on the plot to show the presence of crops

In an agroforestry system, where a plot may include crops such as coffee or cacao, in addition to trees, it may be of interest to indicate the cells where crops are planted, and to determine the distribution of their shades- not on the ground, but at the average height of the plants of the associated crop. Both options are possible by placing **flags**, which enable us to:

1. Indicate the presence of objects (crops) that do not project but receive shade
2. Calculate the distribution of shades at a certain height above ground level

To place flags on the plot you must first activate the Flag status of ShadeMotion by clicking on the red flag icon on the Tool Bar. Once you have activated the Flag status, you can place the markers or flags by using either of the two buttons of the mouse or else by pressing <Enter>. The arrow keys and the yellow point remain available to locate the cells.

To determine the distribution of shades at a given height “h” above ground level, you must assign a value to the height “h” of the flags in the Properties Simulation window. ShadeMotion will then calculate the distribution of shades at a height “h” above ground level for all the cells of the plot, and

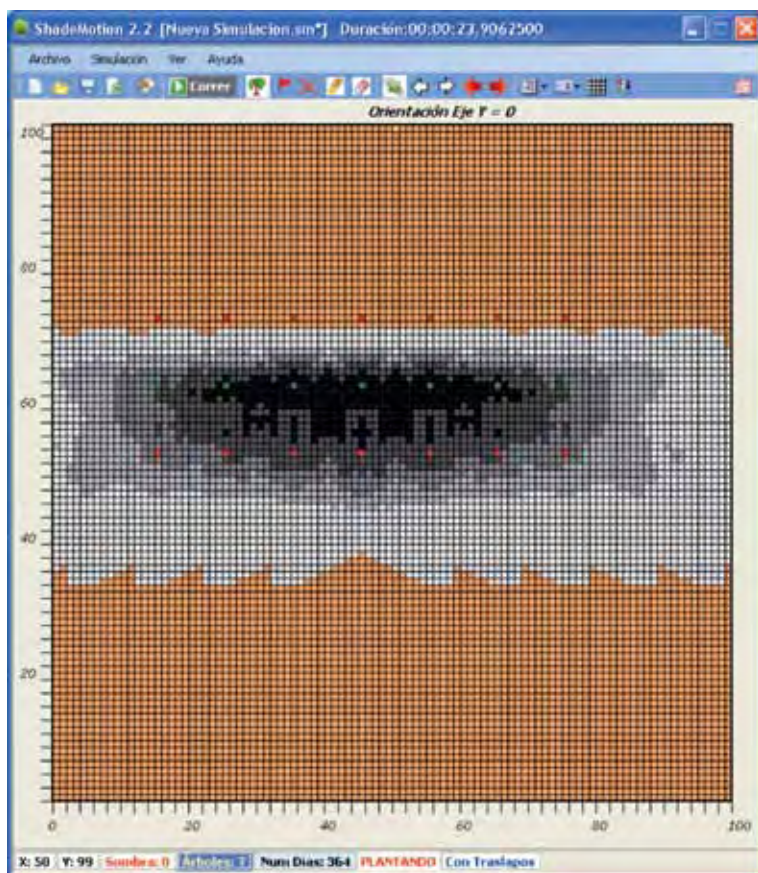


Figure 15. Shows the shade patterns for a row of trees 20 meters high, during one year, at Latitude -20 (20 degrees South of the Equator). Rows of flags (red dots) have been placed at a distance of 15 meters on both sides of the tree rows, representing an associated crop, 4 meters tall. Shade pattern corresponds to 4 meters above ground level. You can see that one of the rows of flags does not receive any shade during the entire year.

not only for those where flags are present. The following restrictions should be borne in mind:

1. All flags must be of the same height.
2. The height of the flags must be less than the smallest trunk height on the plot.
3. Flag height must be a positive number or zero.
4. On plane, tilted plots, flag height is measured vertically and not in a perpendicular direction to the plot.

The default value for the height of the flags is zero (0) and corresponds to the distribution of shades at ground level.

Example 4. Placing flags on the plot

Clear the plot and plant 10 identical trees in any area. The idea is to place flags four meters high, and therefore we must ensure that no tree has a trunk less than four meters in height. Adjust the range of the simulation period to two months. Adjust the daily range of the simulation from 8 a.m. to 5 p.m.

To place the flags proceed as follows:

1. Click on the Flag icon on the Tool Bar to activate placing flags.
2. In the Properties Simulation window enter: Flag height = 4 (meters).



3. Using the mouse or the arrow keys, place five flags at different points on the plot.
4. Run the simulation and examine the shade patterns obtained.
5. Click on the Remove Shades icon of the Tool Bar to erase the shades without removing the trees or the flags.
6. Change the height of the flags to the value 0.
7. Run the simulation again—the new shade pattern should show some differences with respect to the previous one. If you cannot perceive the differences, a way to compare both patterns is copying the main window after each simulation (click on the screen and type <Alt> and <Impant>) and copy image in document with the “Paste” option in the Editing menu or the <Control> + <v> keys simultaneously.

To remove flags from the plot proceed in the same way as for erasing trees: activate the Erase status by clicking on the “X” (Remove) icon on the Tool Bar and place the mouse pointer or the yellow point on the flag you wish to eliminate. Remove it by pressing either one of the mouse buttons or using the <Enter> key. To eliminate all trees and flags from an entire area, simply drag the mouse pointer over the desired area, as if it were the eraser of a pencil, while holding down the right button of the mouse.



Suggestion

Large areas of the plot can be flagged by using the mouse as if it were a pencil. To do this, hold down the right button of the mouse and then drag it over the area that you wish to mark.



7. Projection of shades onto tilted plots

In order to determine the position and distribution of shades on a plane, tilted plot, the value of two new parameters must be specified:

1. The inclination angle of the plot
2. The angle of orientation of the slope

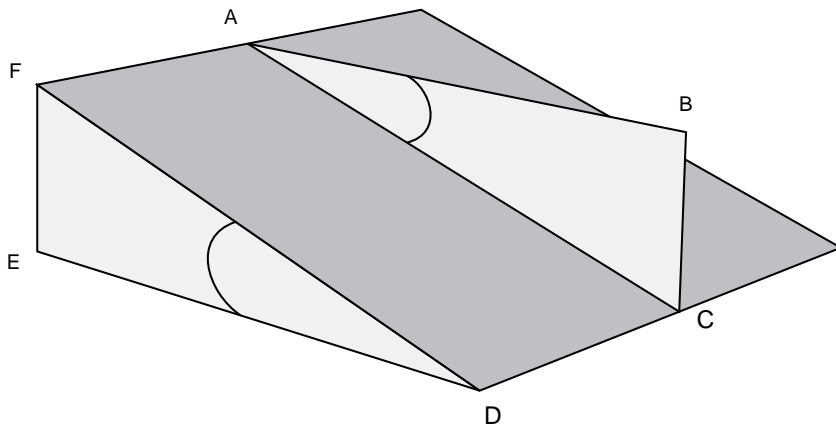


Figure 16. The inclination angle of the slope EDF is equal to the angle CAB. This angle is calculated by measuring the ratios of the lengths of lines BC and AB.

Maximum inclination angle. We know that when someone walks up a tilted plot following a straight line, the effort required to climb the slope depends on the direction of the trajectory. We also know that there is a direction in which slope and effort are maximal. The inclination angle is the angle that forms a line of maximum inclination with the horizontal plane¹. The value of the inclination angle ranges from 0° to 90° , excluding the latter value, which would correspond to a vertical plane.

In the field, the angle of inclination angle can be measured by using a level, a measuring tape, a plumb bob and a piece of string. To measure this angle, visually determine the plot's

¹ There are infinite lines of maximum slope in an inclined plot, but they are all parallel to one another.



direction of maximum inclination; this would be line AC in Figure 16. Following this direction, tie the two ends of a string to two trees or stakes, but keep the string in a horizontal position (use the level here). The line AB in Figure 16 represents the horizontal string. Next, measure the descent of the land using the plumb bob, as given by the length of the line BC. The ratio BC/AB (“rise over run”) measures the tangent of the angle of maximum inclination; therefore this angle is obtained as the inverse tangent or arctangent of that ratio.

Orientation angle of the slope. To fully determine the geographic position of a tilted plot, it is necessary to specify the cardinal direction toward which its lines of maximum inclination point. The angle formed by those lines with respect to North is called the “angle of orientation of the slope.” This angle is measured clockwise, starting from the North and until a descending line of maximum inclination is found (Figure 17). The angle of orientation of the slope may have values from 0° to 360° degrees. According to this criterion, a slope facing North has an angle of orientation of 0° , facing South of 180° , facing East of 90° and facing West of 270° .

To measure the orientation of the slope you only require a compass. Place the compass in a horizontal position and measure the angle by

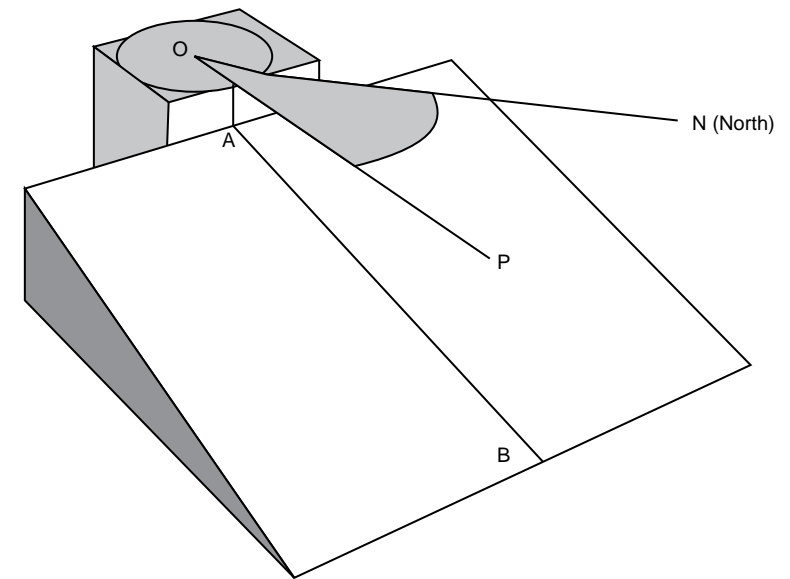


Figure 17. The orientation angle (NOP) of the slope. Lines ON and OP lie on an imaginary horizontal plane. Line AB—which is a line of maximum inclination—and horizontal Line OP lie on an imaginary vertical plane.



turning it clockwise, starting from North, until the compass marker lines up with the descending direction of maximum inclination. In ShadeMotion all angles must be entered in degrees, but their fractional parts (minutes and seconds) should be entered as decimals.

Direction of the Y axis of the grid

For the correct interpretation of shade patterns in a simulation, it is important to be clear about the direction in which the grid's Y axis is pointing.

- For horizontal plots: the positive part of the grid's Y axis always points North.
- For tilted plots: the Y axis is parallel to the lines of maximum inclination and its positive part points in the descending direction of these lines. It is important to pay attention to this detail to avoid confusion, because each time a new orientation of slope is selected, the coordinate axes are adjusted in a direction parallel to the maximum inclination and the shades will apparently move in a new direction within the grid. Measured clockwise from the North, the direction in which the positive Y-axis points is shown in the upper part of the plot grid.

Distortion effects

When the sun's rays strike "on" or "against" the lines of maximum inclination, the shades lengthen or shrink according to the angle of the sun's rays with respect to the plot. However, they remain symmetrical with respect to an imaginary line that runs from the cell where the tree is planted to the center of the shade. When the sun's rays strike in a different direction, this symmetry is lost and the shades show a distortion effect with respect to that imaginary line.

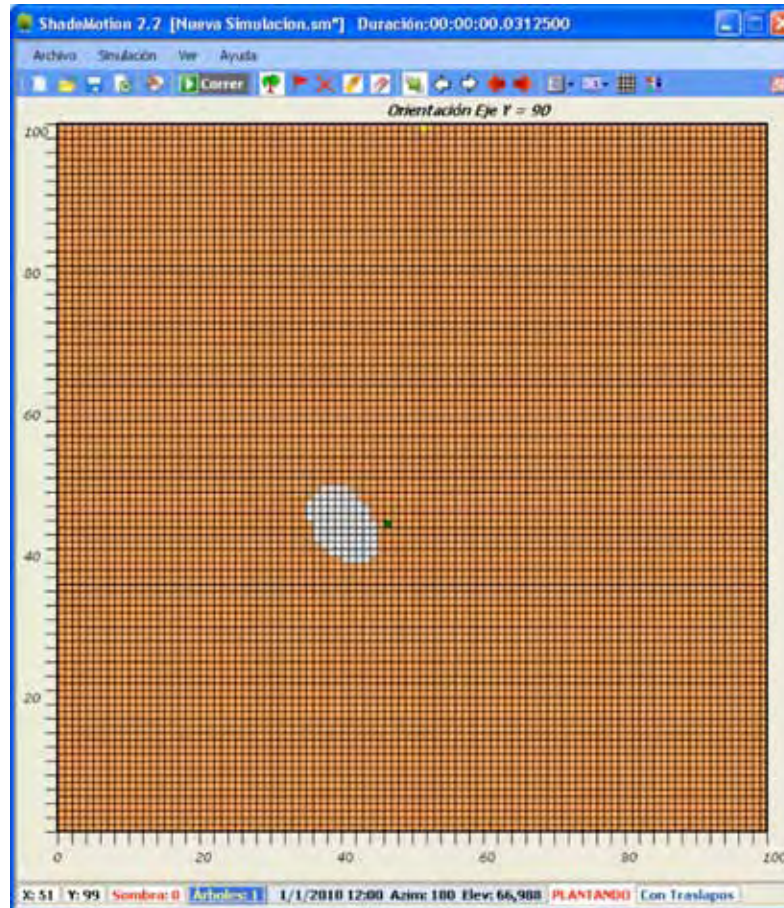


Figure 18. Shade of a tree crown on a plot where the maximum inclination is 45° facing East. The Y axis of the grid also points East. The shade does not remain symmetrical with respect to a line that runs from the small green cell to the center of the shade, as a consequence of the distortion effect that affects shades on tilted plots.



8. Units of time and length

Time unit and computing time for a simulation

In ShadeMotion the time unit is what determines how often the position of the sun and the shades are recalculated during a simulation. This element, found in the Simulation Properties window, is measured in hours and the default value is one hour. However, it is possible to choose other values for the time unit. The lower its value, the more often the position of the sun and the shades will be recalculated and as a result, the computing time increases rapidly. Time units less than one hour should be expressed in decimals, for example, one half-hour would be expressed as 0.5 and 10 minutes as 0.166 ($10/60 = 0.166$). A simulation with a time unit of fifteen minutes would take four times longer than if the time unit were one hour. Regardless of the time unit chosen by the user, the totals of shade accumulated in the cells of the grid are always converted into hours—both when displayed on the screen and when stored in files.

When using small time units care must be taken, as these simulations take a lot of computing time. The calculation of semi-ellipsoidal or conical shades takes more computing time than ellipsoidal crowns, because more mathematical conditions must be verified. The use of tilted planes also increases computing time. The time taken by a simulation is displayed in the upper part of the main ShadeMotion screen, to the right of the word “Duration”, once the simulation has finished.



How to change the plot size

All the previous examples used a plot measuring 100x100 u.l. The ShadeMotion program offers two additional size options: grids with 50 and 200 u.l. per side. In all cases, the grid occupies the same area on the computer screen. What changes is the size of the cells. In order to change the plot size, click on the “Plot Size” icon on the Tool Bar and select the desired option.

How large a plot can be simulated in ShadeMotion?

If we wish to work with the largest plot size possible, we must use the 200 x 200 u.l. grid. If we interpret the unit of length as one u.l. = 1 meter, this gives us a plot area of 200 x 200 = 40,000 square meters, equivalent to four hectares. If we double the unit of length so that 1 u.l. = 2 meters, each cell in the grid will measure two meters per side and have an area of four square meters (4 m²). The entire grid will measure 2 x 200 u.l. = 400 u.l. per side and its area would be 400 x 400=160,000 square meters (16 hectares). The data for the trees must also be calibrated for these new units: each “old” measurement in meters must be halved. For instance, if the height of a crown is 8 meters, in the new units it should measure 4 u.l. given that 4 u.l. = 4 x (2 m) = 8 m.

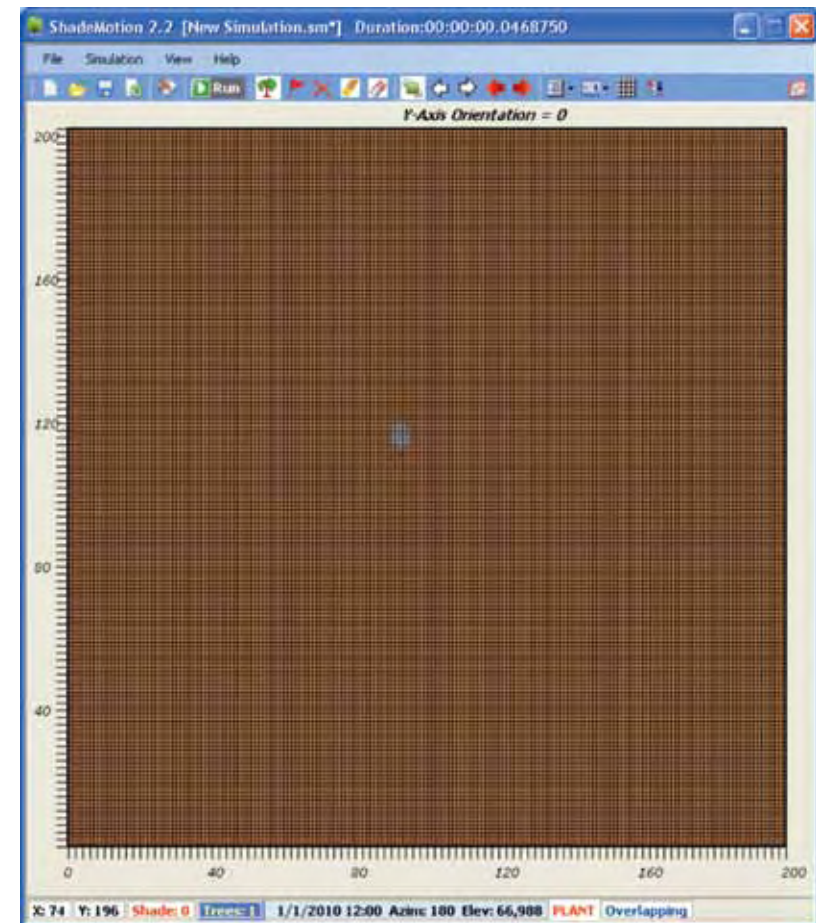


Figure 19. View of a plot measuring 200 x 200 u.l. with the shade of one tree.



By using the trick of duplicating the units of length, it would be possible, in principle, to increase the plot size indefinitely. Each time the unit of length is doubled, the area of each cell on the grid and the plot size is quadrupled. However, a problem arises here: the cells are the “points” that ShadeMotion uses to display the shades and the program has only two options, “fill in” or “do not fill in” the cells; it is not possible to “half-fill” a cell. If we continue to increase the size of the plot (and of the cells), we will soon reach a point where the size of the shade is equal to or less than the area of one cell. In this case, we will have sacrificed precision with respect to the representation of the shade. If we use cells with 2 meters per side, as in the previous example, we will be working with a 16-hectare plot, where each cell has an area of 4 m^2 —which is still acceptable in many cases. A further duplication of the unit of length would increase the plot size to 64 hectares (quadrupling the area again: $16 \times 4 = 64$), but now each cell would be four meters per side with an area of 16 m^2 . It is up to the user to decide how much to increase the area at the expense of precision in the representation of shades.



Rule for changing units of length

If you multiply the units of length by a factor k , the plot and cell areas will increase by a factor k^2 and all tree parameters should be multiplied by the inverse factor $1/k$.

Calculation exercise

Suppose you are working with a 200×200 u.l. plot and decide to use a new unit of length where one u.l. = $1.5 \text{ m} = 3/2 \text{ m}$. Indicate the new sizes of the plot and the cells. If a tree has a crown width of eight meters, also express this value in the new units of length.

Answer. The plot will now measure $200 \times 1.5 = 300$ m per side, a total area of $300 \times 300 = 90,000 \text{ m}^2$ (nine hectares). Each cell now measures 1.5 meters per side and has an area of $1.5 \times 1.5 = 2.25 \text{ m}^2$. All tree parameters must now be multiplied by the inverse of $1.5 = 3/2$, which is $2/3$. Thus, the width of the 8-meter tree crown is now entered as $8 \times 2/3 = 16/3 = 5.33$ u.l.



9. How to export simulations to Excel and how to load files with comma-separated values (csv)

How to export simulations to Excel

Data from the simulations can be exported to Excel files using the appropriate option on the File menu of the Menu Bar, or by clicking on the Excel icon in the Tool Bar. When a simulation is exported to Excel, two files are generated. The first file contains all the input data (the data entered by the user) and the other contains the output data (the list of Cartesian coordinates of the cells and their respective total hours of shade). These totals are displayed in two separate columns which correspond to “With Overlap” and “Without Overlap” options. In order to make the latter file lighter, only the cells with non-zero shade values are included in the list.

The example shown below will help explain this more clearly.

Let us suppose that you have constructed a plot simulation with a certain number of trees and you have now saved it in the ShadeMotion format under the name **plot.sm**. You can only choose a name for a simulation when you save it in ShadeMotion own format (extension “.sm”). Let’s assume that after saving the simulation in “.sm” format, you decide to export it to Excel. When you do this, two files are created whose names are automatically assigned by the program, using the name from the “.sm” file as the root. In this example, the names of these two files would be: **plotproperties.xls** and **plotshade.xls**. The first file contains all the input data from the simulation: the coordinates for each tree; their crown types and sizes; the density and monthly variation in crown foliage;



starting and ending date and time; latitude; time- unit; flags height and position; and the slope and orientation of the slope. The file **plotshade.xls** is reserved for all the output data, i.e. the total hours of shade accumulated in each of the cells that received shade, both with and without overlaps. If you wish to open a simulation again, you should save it in its own ShadeMotion format. The two Excel files created by ShadeMotion can only be opened with the Excel program and not with ShadeMotion.

How to prepare a simulation in a CSV-type file

When you wish to build a simulation with data taken in the field, it is very useful to enter this data in an Excel spreadsheet or a text file, using the format known as “comma-separated values,” whose file extension is CSV. ShadeMotion can load CSV-type files. The important thing in preparing a CSV-type file is sticking strictly to the order in which the data is to be made available, without adding or deleting any columns. The idea of a CSV file is that it does not have any format, other than that introduced by using the space bar and the <Enter> key; the latter is used to indicate the end of a record (in this case a record contains the data corresponding to a single tree). Failure to comply with either of these two principles will have one of the following consequences: the file will be rejected by ShadeMotion (due to incompatibility with the expected format), or the simulation will run using incorrect data (producing false results). Below we present the format that the CSV file should have. If the file is prepared in Excel, starting with cell A1 in the first row, enter the following names, one in each column with no separations by commas. The next example shows the separation between the Excel columns with the “/” symbol.



**X / Y / CrownShape / CrownWidth / CrownHeight / TrunkHeight / Density / Jan / Feb / Mar / Apr / May / Jun
/ Jul / Aug / Sep / Oct / Nov / Dec**

The data for the first tree are placed on a new line, beginning with cell A2:

50,50,Elipsoidal,3,5,4,90,100,100,100,100,100,100,100,100,100,100

The data for the next tree are entered in cell A3, and so on.

Note that the global data of the simulation (starting and ending dates and times; latitude; plot slope; etc.) are not specified in a CSV file. You can adjust these data to your liking when you load the file into ShadeMotion. Finally, so that ShadeMotion can read the Excel file, it should be saved in CSV format. If the file is prepared on a word processor, commas should be used to separate the columns. Do not force a line change with the <Enter> key until all the data for the tree have been entered, as shown below:

**X / Y / CrownShape / CrownWidth / CrownHeight / TrunkHeight / Density / Jan / Feb / Mar / Apr / May / Jun
/ Jul / Aug / Sep / Oct / Nov / Dec (a forced line change here)**

50, 50, Ellipsoidal, 3, 5, 4, 90, 100, 100, 100, 100, 100, 100, 100, 100, 100, 100 (new line change)

and so on, until all the trees are entered.



Descriptors such as “Crownshape” must consist of a single word; for example, “Crown Shape” would be interpreted as two descriptors and would produce an error. The file must be saved as unformatted text; otherwise, ShadeMotion cannot load it.



10. The sun's position in the sky

In ShadeMotion the position of the sun is determined from the **horizontal coordinates** (other types of coordinates are used in astronomy and navigation). Horizontal coordinates are best adapted to the way people on Earth perceive the position of the sun and stars. These coordinates are the angle of elevation and the azimuthal angle. Both angles depend on the day of the year, the hour of the day and the geographic latitude of the observer.

The **angle of elevation**—also known as solar altitude or height—is the angle formed by the horizontal plane and a line joining the observer with the sun (angle RPS in Figure 20). The **azimuth** is the angle between a vertical plane containing the North-South line and a vertical plane containing the sun and the observer. In ShadeMotion the azimuth is measured clockwise from the North². According to this criterion, the azimuth 0° corresponds to North, 90° to East, 180° to South and 270° to West.

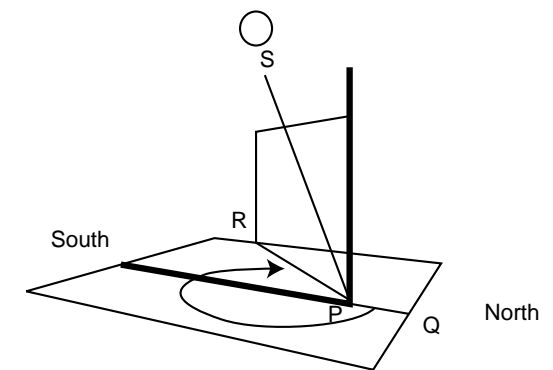


Figure 20. Horizontal coordinates of the solar position. The elevation is the angle RPS. The azimuth is the angle QPR (marked by the curved arrow). The drawing shows an azimuth between 180° and 270° degrees (with the sun on the South side of the sky), corresponding to a time after midday.

² There are also other criteria for measuring the azimuth.



11. Some “cosmetics”

Changing colors (trees, flags and plot)

The Tree Properties window has a dialogue box for selecting the color of the cell where the tree is planted. Each tree may have its own color to represent different tree species, for example. It is also possible to change the color of the flags and the background color of the grid, including the color of the lines that demarcate the cells. Clicking on the Color Configuration icon opens a window that allows you to change any of these elements. Unlike trees, all the flags must be of the same color. If you are not satisfied with the new colors selected and prefer to return to the original ones, select the Restore Defaults option in this window. It is also possible to show or visually eliminate the lines of the plot grid by clicking on the Show/Hide lines button (Figure 21).



Figure 21. Icons for changing colors.



Three types of shading

Click on the Shading icon to choose from three shading contrasts to view the results of a simulation. The Uniform option generates a map with shades in a uniform grey tone, without losing any numerical information about the total hours of shade accumulated in each cell. The Contrast 1 option produces a graded map in which the cells become progressively darker as the number of hours of shade increase. Contrast 2, the default option, divides the shaded areas into five zones (quintiles). You can move from one option to another without having to run the simulation again.



12. Basic assumptions underlying ShadeMotion

Any mathematical model must necessarily be based on some simplifying hypotheses that isolate it from factors that are highly chaotic or very difficult to predict. Consider, for example, the difficulties involved in describing the moment at which clouds form in the sky and predicting the exact shape they will take. Or in accurately modeling the shapes of tree crowns, which consist of thousands of leaves and branches that are in constant motion due to the wind, and have highly irregular shapes due to the growth habit of each species, pruning and other management practices. Below are the basic assumptions underlying the ShadeMotion program.

1. Tree crowns have only three possible shapes: ellipsoidal, semi-ellipsoidal and conical (spherical and semi-spherical crowns are special cases of ellipsoids and semi-ellipsoids in this classification).
2. The shade projected by the trunk is neglected.
3. The program does not take into account the possible presence of clouds in the sky so the simulation gives an indication of the minimum shade value possible (if clouds are present this value would be higher).
4. When computing the sun's position, the effect of the refraction of the solar rays in the atmosphere and the effects of diffuse radiation are not taken into account.



13. Appendix A. Shademotion's computation algorithm in broad terms

The basic cycle

In ShadeMotion time consists of entities called “moments.” A “moment” is a value for the date and hour of the day; together with latitude, this determines the position of the sun. If the hour is increased by a fixed “time-step unit”, it will have passed to the next “moment”, corresponding to a new position of the sun. In ShadeMotion the plot is represented in the computer's memory by means of two square matrices: M and M' , which have as many entries as there are cells in the plot. In each M cell, the total hours of shade received by the cell are computed taking the overlapping of shades into account. In the M' matrix the overlapping of shades is not taken into account. For a given “moment”, the program scans the plot asking whether any tree is projecting shade onto each cell. The question is formulated specifying the moment in time, the tree and the cell. A typical sample question would be:

On May 2, 2009 at 10 in the morning, is the third tree on the list (whose parameters have been specified) projecting shade onto the cell with coordinates (30, 62)?



To answer this question affirmatively or negatively, Shademotion must verify whether the cell (30, 62) satisfies the analytical expressions for the shade that the third tree produces on the specified date and hour. In the affirmative case, the program adds one unit of shade time to the total accumulated in the cell (30, 62) of the M matrix. If no overlaps are recorded it is also added into the corresponding cell of M'. A brief explanation on how these analytical expressions for shades work is given in Appendix B. The program rescans or continually “sweeps” the plot and the list of trees in each new “moment” of the simulation period, until it reaches the final moment. The “sweep” is conducted in the following order:

Cells → trees → time

This means that the program goes over all the cells for the first tree on the list and the first moment of the range of the simulation; then it goes over all the cells for the second tree and so on until completing all the trees on the list. It then increases the time by one time unit and repeats the cycle for the next moment of the simulation: it goes over all the cells for the first tree, then for the second, etc. For any given moment and any given tree, ShadeMotion does not examine the entire plot, but only examines a small, square-shaped area—within which the shade of the tree is found. This considerably reduces the computing time for the simulations.



Version 2.2 of ShadeMotion simulates tilted planes by means of virtual horizontal planes associated with each cell. The plot is visualized as a slope consisting of terraces, so that the cells with equal value of the X coordinate are located at the same height (Figure 22). This decision means having to abandon the convention that the Y axis always points North, but it has the advantage of considerably simplifying the mathematical expressions of the shades and reducing rounding errors. Under the terrace model, asking whether a cell on the tilted plane receives shade from a particular tree is equivalent to asking whether the tree would project shade onto a virtual horizontal plane that passes at the same height of that cell and with the Y axis in the “same direction”³ as the Y axis of the inclined plane. To answer this question, during the calculation, the trunk of the tree must be replaced with an imaginary trunk, which originates at the virtual horizontal plane. The Y coordinate of the point where the tree is located in the virtual horizontal plane must also be adjusted, because the cells of the tilted plane do not coincide with the cells of the virtual horizontal plane under the effects of a vertical projection.



Figure 22. Approximation of a tilted plane by terraces.

³ In other words, both Y axes are in the same vertical plane.



14. Appendix B. Analytical expressions of shades

Position of the sun in the sky

In ShadeMotion the following mathematical formulas are used to calculate the sun's position in the sky:

$$hor = 15 (hora - 12)$$

$$decl = 23.45 \text{ sen } ((360/365) (d + 284))$$

$$elev = \text{sen}^{-1} [\cos(lat) \text{ sen}(decl) \cos(hor) + \text{sen}(lat) \text{ sen}(decl)]$$

$$azim = \cos^{-1} \left[\frac{\cos(lat) \text{ sen}(decl) - \text{sen}(lat) \cos(decl) \cos(hor)}{\cos(elev)} \right]$$

The variables have the following meanings:

- hor = hour angle
- elev = angle of elevation of the sun
- azim = azimuth of the sun
- decl = angle of solar declination
- hora = local time
- d = day (counted from 1 to 365 beginning January 01)
- lat = geographic latitude (positive North of the Equator, negative South of the Equator)



The local hour (time) corresponds to 12 noon when the sun is at its highest point. One o'clock in the afternoon is hour 13 and so on successively. The hour angle “hor” increases 15° degrees every hour and its value is 0 when the sun is at its highest point (at 12 noon). It is negative in the morning and positive in the afternoon.

The shade of an ellipsoidal crown

Without going into all the details, we will explain how the analytical expressions of the shades are obtained using the example of a tree with an ellipsoidal crown planted on a horizontal plane. It is a well-known fact that in a system with three perpendicular Cartesian axes X, Y and Z, the analytical expression of a circular ellipsoid—one that is symmetrical with respect to the Z axis—is expressed as:

$$\frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} = 1$$

where “a” represents half the width of the ellipsoid (of the crown) and “b” is half of its height.

The shade that an ellipsoid with these characteristics projects onto a horizontal plane has the shape of an ellipse. The analytical expression of this shade, with respect to a system of perpendicular Cartesian coordinates in the plane X, Y, with the origin placed in the center of the ellipse and the X and Y axes parallel to the natural axes of the ellipse, is the following:



$$\frac{x^2}{a^2} + \frac{y^2}{(bcotan(elev))^2 + a^2} \leq 1$$

where the sign for inequality (“less than or equal to”) also has the objective of including the points inside the ellipse (for details on how this formula was obtained see: Quesada F, Somarriba E y Vargas E, 1987. Modelo para la simulación de patrones de sombra de árboles. Serie Técnica, Informe Técnico 118. CATIE, Turrialba, Costa Rica. 91 p.). The system of coordinates described earlier, centered on the shade of the tree, is called the Tree Reference System (SRA).

Given that, in general, there will be more than one tree on the plot and that the shade from each tree changes position and shape at each moment of time, the need arises to refer all the shades to a single fixed system of coordinates, regardless of the position of the trees on the plot, as well as the date and the hour. This reference system is known as the Universal Reference System (SRU). The task then consists of converting the expression for the elliptical shade from the Tree Reference System SRA to the universal system SRU. This can be done using an intermediate system of Cartesian coordinates that we will call the SRB system.

The SRB system has its origin of coordinates at the same point as SRA, in the center of the shade, but with its axes pointing in fixed directions: the positive part of the Y axis points North (and therefore the positive part of the X axis points East). The conversion of SRA to SRB is done using



a rotation of the coordinate axes of SRA around the origin⁴, until the positive Y semi - axis points to the North. The magnitude of the angle that must be rotated is equal to $azim + 180^\circ$, since the shade always has an “angular displacement” of 180° with respect to the sun, i.e. always lies on the sun’s opposite direction.

The axes of the SRU system are parallel to those of the SRB system (its positive Y semi-axis also points North) but the origin of SRU is located in the southwest corner of the plot (on the screen this corresponds to the lower left corner of the grid). Figure 23 shows the three reference systems in the case of an elliptical shade.

We will now see how these changes of coordinates affect the inequality that expresses the crown’s shade in the SRA system.

As mentioned previously, the SRA system is converted to SRB through a rotation of the coordinate axes. A rotation by an angle of $azim + 180^\circ$ transforms the coordinates from a point (x, y) with respect to SRA in its coordinates (x', y') with respect to SRB as follows:

⁴ In other words, around an imaginary axis that passes through the origin of the SRB system and is perpendicular to the XY plane.

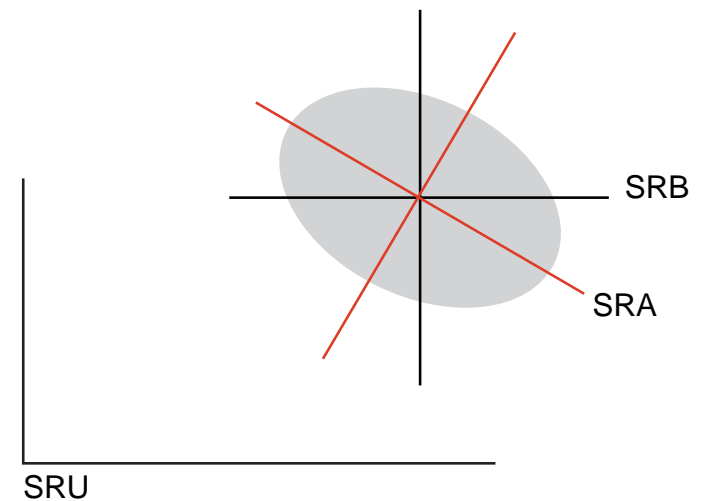


Figure 23. The three reference systems in the case of an elliptical shade



$$x = x' \cos(\text{azim} + 180) - y' \sin(\text{azim} + 180)$$

$$y = x' \sin(\text{azim} + 180) + y' \cos(\text{azim} + 180)$$

By replacing these expressions in the inequality of the shade with respect to SRA we obtain the following expression in SRB:

$$\frac{(x' \cos(\text{azim} + 180) - y' \sin(\text{azim} + 180))^2}{a^2} + \frac{(x' \sin(\text{azim} + 180) + y' \cos(\text{azim} + 180))^2}{(b \cotan(\text{elev}))^2 + a^2} \leq 1$$

In the SRU system, (x_0, y_0) ⁵ are the coordinates for the center of the shade. The relationship between the coordinates of a point (x', y') in the SRB and its coordinates (x'', y'') in the SRU system is expressed in the following equations, which describe a translation of the coordinate axes:

⁵ The coordinates of the center of the shade (x_0, y_0) depend on the position where the tree is planted as well as the heights of the trunk and crown of the tree.



$$x' = x'' - x_0$$

$$y' = y'' - y_0$$

By applying these formulas to the expression of the shade in the previous SRB system, we finally obtain the expression of the shade in SRU:

$$\frac{((x'' - x_0) \cos(\text{azim} + 180) - (y'' - y_0) \sin(\text{azim} + 180))^2}{a^2} + \frac{((x'' - x_0) \sin(\text{azim} + 180) + (y'' - y_0) \cos(\text{azim} + 180))^2}{(b \cotan(\text{elev}))^2 + a^2} \leq 1$$

The above inequality will only be satisfied by the cells of the coordinates (x'' , y'') that are found to be covered by the elliptical shade.



15. Appendix C. System requirements for installing ShadeMotion

ShadeMotion 2.2 is open code software, property of CATIE (Tropical Agriculture Research and Higher Education Center), and is distributed freely under the GNU General Public License (GPL).

ShadeMotion 2.2 takes up very little space on the computer drive. The program was developed for Windows using Microsoft's Visual Studio programming environment. For this reason, the computer must have an installed version of Microsoft's .NET Framework. The .NET Framework 2.0 program is included on the CD that accompanies this publication and can also be downloaded from the Internet.

Installing ShadeMotion from the CD

The CD that accompanies this publication has been configured to initiate the installation of ShadeMotion 2.2 automatically. If this does not occur, check the CD and you will see two icons as shown in Figure 24:



Figure 24. Installation of ShadeMotion



Click on the right icon shown in Figure 24 to start the installation. If a version of .NET Framework has already been installed on your computer, the installation of ShadeMotion will begin immediately. Otherwise, the installation of .NET Framework 2.0 will begin and once this is completed, the installation of ShadeMotion 2.2 will follow. All you have to do is follow a few instructions that appear on the screen.

Important recommendation

ShadeMotion version 2.2 is included on the CD that accompanies this publication. To check for an updated version of this program and install it, visit: www.shademotion.com or the CATIE Web page at: www.catie.ac.cr.

Installation of ShadeMotion from the Internet

If you wish to install ShadeMotion from one of the two Internet sites, the process to follow is very similar to the one described above. First, download the ShadeMotion program. However, if the .NET Framework program is not already installed on your computer, the installer will automatically connect to the Microsoft site where you can download .NET Framework 2.0 or a later version. Once this program is installed, you can continue with the installation of ShadeMotion.

ShadeMotion versions for Linux and Macintosh platforms have not yet been developed.



16. Bibliographical references

Bellow, JG; Nair, PKR. 2003. Comparing common methods for assessing understory light availability in shaded-perennial agroforestry systems. *Agricultural and Forest Meteorology* 114: 197-211 p.

Gómez, S; Quirós, C. 2005. SSV3D: Simulador de sombras vectoriales por radiación solar sobre objetos tridimensionales (SSV3D: Simulator of Vectorial Shadows by Solar Radiation on 3-D Computerized Objects). *Información Tecnológica*. La Serena, CL. vol. 16 no. 4: 77-82 p.

McPherson; EG; Rowntree, RA. 1998. *Geometric solids for simulation of tree crowns*. Elsevier. US.

Mialet-Serra, I; Dauzat, J; Auclair, D. 1999. The use of plant architectural models for estimating radiation transfer within agroforestry—an example for multi-strata coconut-based farming system. (Proceedings in international Symposium in Multi-Strata Agroforestry Systems with perennial crops). CR. 194-197 p.