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Simulating the Shading Pattern of Tree Shades Using ShadeMotion 2.0

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Abstract

ShadeMotion is a software designed for modelling the position and movement of tree shades on the ground. The user can choose any spatial distribution of trees within a plot of up to 40,000 square units of length (meters, yards or any other unit of length), as well as the size, height and shape of each tree crown. The plot can be located anywhere on earth. The initial and final dates of the simulation period can also be arbitrarily selected by the user. ShadeMotion will output a graphical representation of the shades on the plot, showing how many hours of shade are accumulated in each cell of the grid. The user can also obtain an Excel file with all the information provided by the simulation. ShadeMotion also allows the user to visually compare the position, shape and size of shades as the sun changes its position during any particular day of the year. ShadeMotion is a stand-alone application that can be downloaded from Internet (http://www.catie.ac.cr), but it requires the previous installations of Windows Netframework in the user's computer. In this workshop we demonstrate the use of ShadeMotion and describe how shade patterns are calculated, both from the mathematical and computational standpoints.

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Resumen en español

ShadeMotion: patrones de sombra arbórea en el suelo

ShadeMotion es un programa de cómputo diseñado para modelar la posición y movimiento de las sombras de árboles sobre el suelo. El usuario puede escoger cualquier distribución espacial de árboles dentro de una parcela cuadrada, con un lado de hasta 40.000 unidades de longitud (metros, yardas o cualquier otra unidad de medida de longitud), tanto como el tamaño, altura y forma de la copa de cada árbol. La parcela puede localizarse en cualquier ubicación de la tierra. Las fechas iniciales y finales del período de simulación pueden ser arbitrariamente seleccionadas por el usuario. ShadeMotion producirá una representación gráfica de las sombras sobre la parcela, mostrando cuántas horas de sombra se han acumulado en cada celdilla de la cuadrícula. El usuario puede también obtener un archivo de Excel con toda la información provista por la simulación. ShadeMotion puede trazar la posición y movimiento de en la pantalla, de tal manera que el usuario puede visualizar los efectos de las formas de las copas y los tamaños, como también los cambios en la posición del sol a través del año y entre horas en un día dado.

ShadeMotion es una aplicación autónoma que puede bajarse desde Internet: http://www.catie.ac.cr, pero requiere de la instalación previa de Windows Netframework en la computadora del usuario. En este taller mostraremos el uso de ShadeMotion y describiremos cómo los patrones de sombra son calculados, tanto desde el punto de vista matemático como del informático.

Introduction

ShadeMotion 2.0 is a computer program that simulates the position and movement of tree shades on the ground while building a graphical and numerical representation of the shade distribution. The program is available in both Spanish and English languages and can be downloaded from the site: www.catie.ac.cr (once in the Web page, type ShadeMotion in the search box and then click on

the appropriate selection to access the software). ShadeMotion version 2.0 deals only with the projection of shades on a flat horizontal plane. Future versions will include the projection of tree shades on tilted planes.

ShadeMotion was conceived as a research tool for agroforestry research and development. It is ideal for testing the shade patterns of different arrays of trees in agricultural fields (for instance, shaded cocoa or coffee plantations, and dispersed or planted trees in annual crop fields) or pastures.

Modeling options

The following list of parameters can be defined by the user when using ShadeMotion.

Tree parameters

1. Any number of trees can be placed in the plot and in any spatial planting arrangement.
2. Crown shapes are limited to five types: spherical, semi-spherical, ellipsoidal, semi-ellipsoidal and conic.
3. Each tree can have its own parameters: trunk height, crown shape, crown height, crown width. This is useful to depict many tree species.

Global parameters

1. Starting and ending dates of the simulation period.
2. Daily (hours) range of simulation (i.e., from 9 a.m. to 4 p.m. each day).
3. Geographical latitude of the plot.
4. Time step unit (how often the position of the sun is to change during the day).
5. Plot size.
6. Units of measure for length and area (meters, yards, etc.).
7. Y axis orientation of coordinate system.
8. Selecting "h" to obtain the shade distribution "h" units above the ground level. (h = 0 means shade distribution at ground level).

Simulation outputs

The program produces two outputs:

1. A graphical representation of the shade cast on the ground presented in the form of a contour map (Figure 1). Darker areas represent more time units of shade cast on the cell. By placing the pointer on any cell, the number of time units of shade accumulated in that cell is shown in the output bar at the lower edge of the ShadeMotion screen.

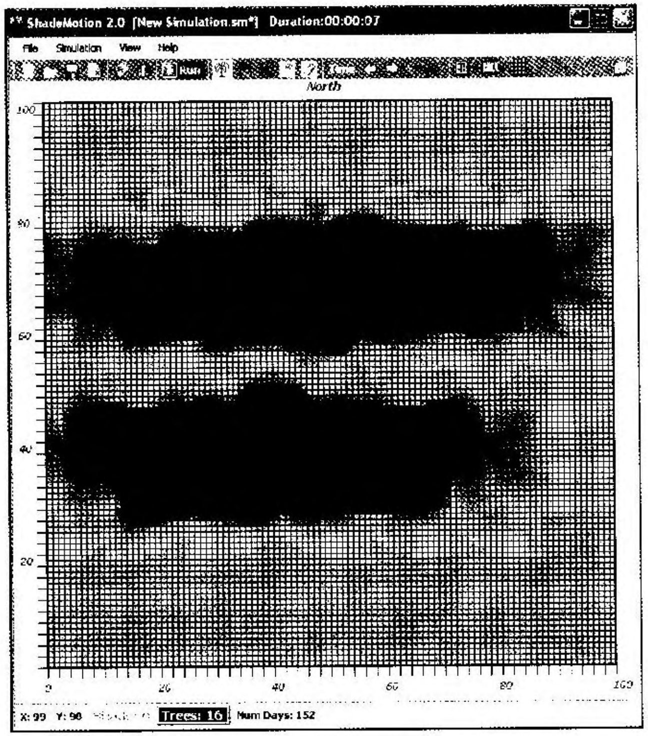

Figure 1. Shading pattern produced by 16 identical trees accumulated over a six-month period (01/01/2008 to 06/01/2008, each day from 7 a.m. to 5 p.m.), at latitude 0°.

2. An Excel file can be produced containing the coordinates of each cell in the grid and the amount of shade accumulated in each cell. This file also contains all the input data used in the simulation (both all tree and global parameters).

By simulating the shade cast by trees on one given day (as opposed to the accumulation of shade over a simulation period as in Figure 1), the user can change the position of the sun at the time interval he/she chooses using arrows provided in the Tools bar. By doing this, the user can track the movement of the shade on the ground and be able to explore the changes in shading patterns for different days in the year or for a given day in different latitudes (Figure 2).

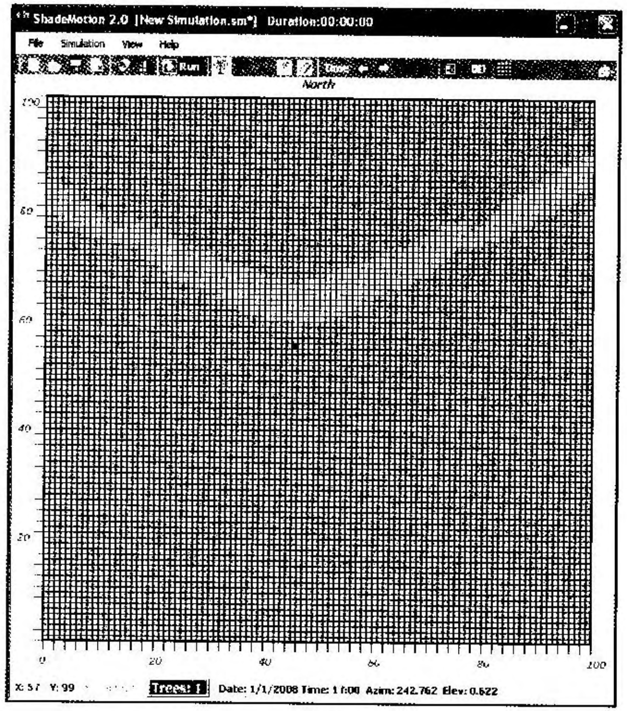

Figure 2. Area swept by the shade of one tree on January 1, from 7:30 a.m. to 4:30 p.m. at latitude 30°.

Basic underlying assumptions

ShadeMotion operates on the following list of basic assumptions:

1. Crown shapes are simple geometrical objects of three possible types: ellipsoidal, semi-ellipsoidal and conic (spheres and semi-spheres are special cases of ellipses and semi-ellipses).
2. Crowns are opaque objects.
3. The shade projected by the tree trunk is neglected.
4. The presence of clouds in the sky is not taken into account.
5. The refraction of solar rays when entering the atmosphere is neglected.

The mathematics behind ShadeMotion

ShadeMotion computes the exact location of the shades cast by the crown of each tree planted in the plot for each position of the sun, as determined by the latitude, day and hour ranges defined by the user. When computing shades, tree crowns, which are solid three dimensional objects, are replaced by flat surfaces (the crown's cross section) opposing the direct trajectory of sun rays (diffuse radiation is not taken into consideration in ShadeMotion). The shade cast by some crown shapes is modeled using two flat surfaces: for example, a conic crown is replaced by a vertical triangle and a horizontal disc, the latter representing the base of the cone.

The position of the sun is computed using horizontal coordinates: elevation and azimuth. The following standard formulas are employed for elevation (elev), azimuth (azim), declination (decl) and hour (hor) angles.

$hor = 15\ (hour - 12)$

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

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

$azim = cos^{-1}\{[cos(lat)sen(decl) - sen(lat)cos(decl)cos(hor)] / \ldots$

$\ldots cos(elev)\}$

When the position of the sun is known, the exact position of a shade is determined on the ground. All shades are expressed with respect to a universal reference system SRU of rectangular Cartesian coordinates. Each cell of the grid (plot) is referenced by a pair of coordinate numbers (x, y) relative to SRU. Two auxiliary reference systems (also Cartesian) SRA and SRB are employed before translating the shade to SRU. Each tree has its own SRA an SRB systems. The origin of SRA is located at the center of the shade and the X and Y axis are parallel to the natural axis of the shade. SRB has the origin also in the center of the shade, but the X and Y axis are parallel to those of SRU. By default, the Y axis of SRU points toward the North. SRA is transformed into SRB by means of a rotation of coordinate axis. An additional translation is needed to go from SRB to SRU (Figure 3).

In order to determine if a cell (i, j) is under the shade of a tree, we must first define an equation that describes the contour of the shade in SRA, then express this equation with respect to the rotated SRB coordinate axis and finally translate the equation to the common system SRU. Let's illustrate this in the case of a tree with an ellipsoidal crown, located at coordinates (x_0, y_0). The contour of the shade projected by such a crown is an ellipse.

The inequality for the interior of such an ellipse in system SRA, is:

$$x^2/\ a^2 + y^2\ /\ [(b cotan(elev))^2 + a^2\ ] < 1$$

where a = crown width and b = crown height

When referring the latter expression to system SRU, the tree coordinates (x_0, y_0) and the azimuth angle must be included. A cell (i, j) is under the shade projected by this tree if the values x=i and y=j satisfy the following inequality:

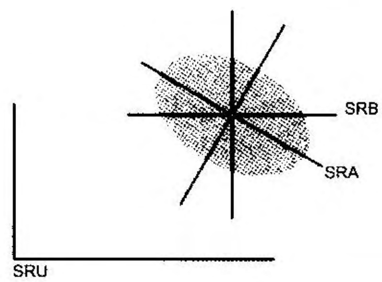

Figure 3. Cartesian coordinate systems used to determine the position of the shade on the ground.

$[(x-x_0)\cos(azim+180) - (y-y_0)\sin(azim+180)]^2 / a^2 + \ldots$

$\ldots[(x-x_0)\sin(azim+180) + (y-y_0)\cos(azim+180)]^2$
$/ \ldots \ldots[(b\,cotan(elev))^2 + a^2] < 1$

Scanning the shades

The plot is internally represented by a square matrix M. The number of entries in M is the same as the number of cells in the plot. Entry n(i,j) of M is an integer which denotes the total amount of shade accumulated in cell (i, j), at any time during the scanning process. When the program scans the plot in search for shades, there are three questions that have to be answered. (1) What is the value of time (day and hour)? (2) Which tree is being processed? (3) Which cell is being scrutinized? The search for shades is performed following the order: cells-trees-time. This means that:

- For a given tree, all cells in a selected region of the plot that contains the shade have to be scanned, before moving to the next tree.
- All trees in the plot have to be scanned before moving to the next time unit.

Each time a cell (i, j), is shaded by a tree, then the corresponding entry n(i,j) of M is replaced by n(i,j) + 1.

When the scanning process comes to an end, entry n(i,j) of M contains an integer which denotes the total amount of time units of shade cast on cell (i,j), by all trees, over the entire simulation period.

Shading at a given height above ground

ShadeMotion provides a means to determine the shading pattern at a certain height above ground. For instance, if the user wants to determine the shade cast over the canopy of coffee plants 2 m in height, the user may set the height parameter at 2 m and ShadeMotion will calculate the shades at that height and not on the ground.