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ShadeMotion: tree shade patterns in coffee and cocoa agroforestry systems

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Abstract Shade trees in coffee and cocoa agroforestry systems provide valuable livelihoods and other ecosystem services. Unfortunately, most shade canopies are sub-optimally designed and managed and the reasons behind this sub-optimality are poorly known. There is evidence, however, indicating that farmers and extension agents lack both the knowledge and access to user-friendly tools to optimally design their shade canopies. To fill this gap, we developed ShadeMotion, a simple to parameterize, yet powerful software, capable of calculating the spatial and temporal distribution of the shade cast by trees on a plot (horizontal or tilted) anywhere on Earth. Trees may be planted in any spatial arrangement, their population density can change according to planting, thinning, mortality or harvest, tree crowns may take any of eight possible, regular, geometric shapes, vary in density and monthly leaf fall patterns, and may be pollarded or not. Shade patterns may be calculated for one instant, 1 year or less, or for the entire life cycle of a plantation; in the latter case, tree growth data must be added as input. Shade can be measured at ground level or at any height above the ground. In this article, we: (1) describe the key features of the software, and (2) simulate the spatial and temporal shade patterns of a traditional agroforestry system of *Coffea arabica* cv. Caturra, *Erythrina poeppigiana* and *Cordia alliodora* in Costa Rica. ShadeMotion can realistically model farm scenarios and may be used in the participatory design of agroforestry systems in farmers field schools and in classrooms.

Keywords Software · Simulation · Tree crowns · Shade levels · Shade density maps · Shade temporal dynamics

Introduction

Coffee (11 million hectares) and cocoa (10 million hectares) are two important commodities; globally 30% of the area planted to each crop is cultivated under shade (Laderach et al. 2017; Orozco-Aguilar et al. 2021). Trees provide shade, shelter, valuable livelihoods, and ecosystem services (Cerda et al. 2014; Pinoargote et al. 2017). Surprisingly, and disappointingly, most tree canopies in cocoa and coffee agroforestry systems are sub-optimal in botanical

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composition (species' uses not matching farmer's expectations), spatial distribution of tree cover, and shade levels. Why do farmers neglect the opportunity to optimally design the shade canopy of their coffee/cocoa plantation to achieve their goals? Why do technicians fail to advise farmers on how to better design their shaded coffee and cocoa plantation to meet their needs? Evidence suggest that farmers and extension agents lack both the knowledge and access to user-friendly tools for the analysis and design of optimal coffee and cocoa shade canopies (Silva et al. 2013).

Numerous studies have been published on the physical (e.g., plant hydraulic design) and ecological (e.g., optimization of solar radiation capture) principles that explain tree and crown architecture and canopy foliage arrangement, tree cover and the amount of shade cast by trees (Côté et al. 2011; Englund et al. 2000; Fiala et al. 2006; Frazer et al. 2001; Guevara-Escobar et al. 2005; Hanan 1997; Hilker et al. 2010; Kato et al. 2009; Korhonen et al. 2006; Kuuluvainen and Pukkula 1987; McPherson and Rowntree 1988; Seidel et al. 2012). Plant physiologists have developed very detailed and accurate 3D plant models to assess both the transmission and interception of solar radiation by crop canopies (Charbonnier et al. 2013; Lamanda et al. 2008; Leroy et al. 2009; Mialet-Serra et al. 2001; Sinoquet et al. 2007; Vezy et al. 2020; Wang and Jarvis 1990), but these models are usually highly complex and highly demanding of field data to calibrate model parameters. Models of intermediate complexity have also been developed (Dupraz et al. 2019). Agroforestry specialists and practitioners, on the other hand, need simple tools to quickly and accurately explore the shade patterns cast by any given planting configuration and management of trees in a plot. To fill this gap, we developed ShadeMotion, a simple, yet powerful, internet based, interactive software designed to quickly explore different tree planting configurations and mixtures of species to help deciding on the best agroforestry designs for a given context.

In this article, we describe the key features of the software and use it to simulate the spatial and temporal shade patterns of a traditional agroforestry system of *Coffea arabica* cv. Caturra, *Erythrina poeppigiana* and *Cordia alliodora* in Costa Rica. The description of the model and software partially follows the ODD protocol (Grimm et al. 2020). Further details of the software can be found in the tutorial (Somarriba et al. 2020); mathematical details are given by Quesada-Chaverri (2021).

Materials and methods

Description of the software

ShadeMotion is a software application that calculates the spatial and temporal distribution of the shade cast by trees on a plot. Tree canopies are constructed by planting any number of trees, in any spatial arrangement, anywhere on Earth, on horizontal or tilted planes; trees may grow or not, and their populations may remain constant or change due to thinning, mortality, harvest, or planting. Trees can be planted in systematic spacings, distributed randomly in the plot, or planted in any other spatial arrangement. Tree crowns are represented by geometric objects of eight different shapes: spheres, semi-spheres, ellipsoids, semi-ellipsoids, umbrellas, cones, inverted cones, and cylinders. The blocking of sun rays by tree crowns is determined by both crown opacity and monthly leaf fall patterns; trees can be pollarded or not (if pollarded, monthly growth rates in crown diameter must be given as input). Shade maps can be computed for a snapshot, one full year (or less), or over the entire life cycle of a plantation (tree growth data must be provided). Shade can be recorded at ground level or at any height aboveground (e.g. at the height of a crop's canopy). A summary of the input data required to run simulations in ShadeMotion is listed in Table 1.

Contour maps of the number of hours of shade, summary statistics, and data files containing shading information for every cartesian coordinate point in the plot are generated and can be saved to a (usually very large e.g. up to 10^9 registers) file. Spatially explicit shade data generated by ShadeMotion can be used for distance-based competition analyses or for the statistical analysis of shade spatial patterns that may be of biological relevance, for instance, to the dispersal of pest and pathogens and crop yields (Gidoin et al. 2014). Visualization tools allow users to see the movement of shadows on the ground as the sun changes position in the sky or as tree crowns develop (hence the "motion" element in the name of the software). Installer and tutorials (in English, French, Spanish, Portuguese, German, and Mandarin Chinese) can be downloaded from www.shade

Table 1 Input data required to run a simulation in ShadeMotion

Tree and crop data
Tree and crop species names
Tree crown shape (eight geometric shapes available for selection for each tree)
Cartesian (x, y) or GPS (latitude, longitude) coordinates to indicate the position of each tree in the plot
Tree diameter at breast height by age (cm)
Tree trunk height by age (m)
Tree crown height by age (m)
Tree crown diameter by age (m)
Tree crown diameter by month for pollarded crowns (m)
Crop height by age (m)
Solar movement data
Start date of simulation (dd/mm/yyyy)
End date of simulation (dd/mm/yyyy)
Start hour every day (hh:mm)
End hour every day (hh:mm)
Time step (minutes or hours)
Plot data
Latitude (in degrees, minutes, seconds), negative values for Southern latitudes
Plot length (m)
Plot width (m)
Azimuth of plot's Y-axis (degrees, clockwise from Earth's magnetic North)
Slope (degrees)
Azimuth of maximum slope (degrees)

motion.net to a device (Windows, Mac, Linux). Simulations can also be run online. In what follows we describe the key elements of the software.

For an observer at any location on Earth, the position of the Sun, in horizontal coordinates, is defined by two angles: azimuth (*azim*) and solar elevation (*elev*). These angles are determined by the geographic latitude of the site (*lat*), the day of the year (*day*, day 1 is January 1st), the local time of the day (*hour* in a 24-h scale; this angle ranges between $-180°$ to $+180°$ at a rate of 15 degrees per hour), and the solar declination (*dec*). Latitude has a negative sign in the Southern hemisphere. The equations for the solar declination, solar elevation, and azimuth angles follows Sellers (1965). The software calculates these angles for every "simulation instant", defined by the range of days (e.g. January 1 to December 31), range of hours per day (e.g. 08:00 to 16:00), and the time step (e.g. every 15, 30, 60, 120 or 240 min) defined by the user. For instance, one full year (365 days), from 8 am to 4 pm (9 h i.e. extremes are included) at 1 h steps will result in $365*9*1=3285$ simulation instants. Changing the time step to 15 min will result in 13,140 simulation instants.

Light passage through the crown is modeled by combining: (1) a simple estimate of crown opacity ($0 \leq \text{opacity} \leq 1$, 0 for completely transparent crowns and 1 for completely opaque crowns), and (2) a monthly leaf fall pattern ($0 \leq f \leq 1$). The product opacity*monthly leaf fall estimates the fraction of shaded area in a shadow. At every simulation instant, a random number generator is used to define the position of "light holes" in a shadow, prior to plotting the shadow on the ground. The size (grain) of the "light hole" can be changed by changing the size of the grid cells in the terrain.

The terrain is represented in the first quadrant of the Cartesian plane. As default, the positive Y axis is oriented to the north of the Earth, but this azimuth can be changed by the user to facilitate measurement of tree position in the field. The terrain is decomposed into a grid and each grid cell is associated with a unique pair of Cartesian coordinates (*x*, *y*). The size of the grid cells can be defined by the user (a 1 m×1 m grid cell is provided as default);

tree dimensions and plot size must be scaled to the grid cell size used. Default tree, crop, and plot dimensions are in meters. However, any other unit can be used, provided all measures are scaled to this unit (for instance, with 0.5 m units, a 10 m crown diameter will be entered as 20; a 50 m×50 m plot will be represented as a 100×110 plot with 0.5×0.5 m grid cells). Shadow patterns can be simulated for both horizontal and tilted terrains (Fig. 1).

The analytical expression of a shadow is given by mathematical inequalities (Appendix 1), some of which and for certain geometric figures are grouped together to form systems of inequalities (Quesada-Chaverri 2021). Inequalities, unlike equalities, include not only the points on the shadow contour but also the points inside the contour. Three Cartesian coordinate systems are used to derive the analytical expressions of a shadow (Fig. 2): (1) A SRA system whose origin is at the center of the tree's shadow, with its axes parallel to the axes of symmetry of the shadow; (2) A SRB system with the same origin as SRA but with its axes rotated (θ) so that they are parallel to the axes describing the plot; and (3) A SRU system with origin located at the lower left corner of the plot grid. It is with respect to SRU that the inequalities of all shadows are expressed.

The set of pairs of Cartesian coordinates under the shadow cast by a crown is determined in two steps: (1) delineating the contour of the shadow using a Moore's Neighborhood algorithm (Reddy et al. 2012; Sharma et al. 2013), and (2) sweeping all the cartesian coordinates within the shade contour and storing the coordinates of all shaded grid cells in a data buffer. The strategy for calculating the mathematical expressions of shadows on inclined planes takes advantage of the calculations for horizontal planes, modeling the tilted plane as a "grid" of horizontal strips or bleachers (Quesada-Chaverri 2021).

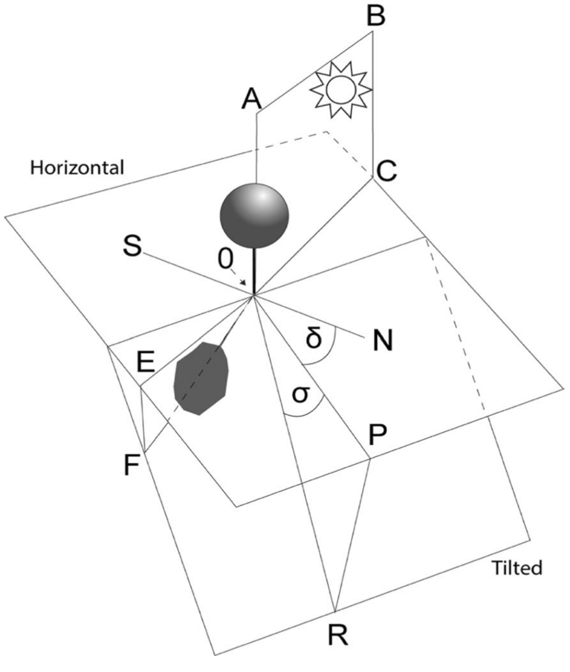


Fig. 1 Planes and angles involved in the projection of the shadow on horizontal or tilted planes. The letters N and S stand for North and South, the line EC does not necessarily match the East West direction. Vertical plane OABC contain any solar ray landing at the tree crown center. Section OFE is also part of vertical plane OABC. Angle δ indicates the direction in which tilted plane is facing. Line OR is the intersection of vertical plane OPR with the tilted plane and tan(σ) measures the slope of this plane. Tree shadow twist with respect to line OF in tilted terrains

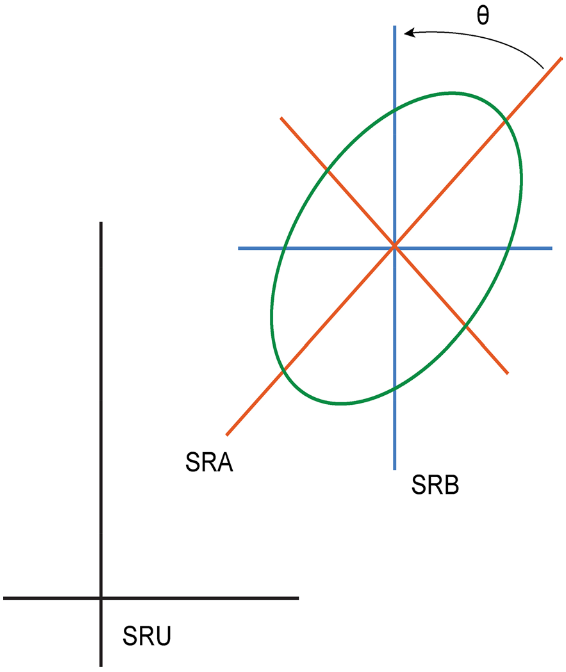


Fig. 2 Cartesian coordinate systems SRA, SRB and SRU applied to an elliptical shadow. The angle θ shows the angular amount by which the axes of the SRA system must be rotated to obtain the SRB system. By default, the Y+semi-axes of the latter two systems point in the north direction, but this direction can be changed by the user

The code in ShadeMotion was written in Javascript version ES6 and designed to meet four functional requirements: (1) capable of running on Windows, Linux, and Mac; (2) have a user-friendly graphical interface; (3) high speed; and (4) capable of running online or offline. This application uses software development technologies such as HTML5, CSS3, ECMA Script 6 (which belong to the web presentation layer) to meet all functional requirements, provide the possibility to develop a software that is extensible, scalable, maintainable, fast, intuitive, accurate in its calculations, and generate high quality reports. The core of the code consists of a VueJS application that can be executed both from a web browser, as well as natively embedded within the ElectronJS platform (for installable versions), allowing it to be portable to different operating systems. The embedding within ElectronJS makes the system run using the Chromiun engine. This ensures that installable versions run consistently. ShadeMotion runs in any operating system with Google Chrome v88 (or higher) browser. Program size is 15270 lines of code, and it is stored in Bitbucket.

The modular architecture of the code is based on the reactive functional programming paradigm, which enables the composition of core functionality as relatively independent sampling operations that can be individually tested and optimized. The JSON format is used to exchange information between modules, and to store and report results at the end of a simulation. The code is divided into modules that are grouped into three main areas: (1) Simulation objects: Groups the entities that make up the simulation, including terrain models, trees, leaf fall and tree growth tables, species catalog, and time parameters, among others; (2) Controllers: Includes all sampling operations, for example: sun position, simulation moments, generation of clusters of trees with the same crown characteristics, shade equations, crown contour tracing, random patterns of light holes, as well as shading and report generation; and (3) Graphical interface module: including on-screen display components, as well as the handling of interactions with the user, and 3D visualization. A key aspect in the development of the code was the use of unit tests (Gren and Antinyan 2017). The overall coverage of unit tests in the development of code was 32%, although for some individual software components, the coverage exceeded 90% (e.g., 100% coverage in the cluster generator).

Characteristics of the coffee-poró-laurel agroforestry system

In Turrialba, Costa Rica, coffee (*Coffea arabica* cv. Caturra) is planted with two shade species, which form two vertical shade layers: a high layer 25–30 m tall, with laurel trees (*Cordia alliodora*) and a low layer 3–6 m tall, with poró (*Erythrina poeppigiana*). Laurel (Boraginaceae) is a timber species and is not pruned; poró is a nitrogen-fixing legume pollarded twice a year (January and June). Coffee bushes are planted at 5000 plants ha^{-1}, spaced at 2 m×1 m. Poró trees are planted by stakes 2–3 m long, spaced at 6 m×6 m (278 trees ha^{-1}). Laurel trees are either planted (typically at 12×12 m, 69 trees ha^{-1}) or recruited from the natural regeneration and constantly thinned to both eliminate dense patches and to regularly space the trees, attaining between 50 and80 trees ha^{-1} (Llanderal 1998).

Coffee bushes of the Caturra cultivar are short, reaching a maximum height of 2 m at the age 4 years, starting from 0.5 m in 1 year old plants, 1 m at age 2 years, and 2.0 m from year 3 onwards. Pollarded poró trees have a spherical crown on a 3 m tall trunk. Crown diameter of poró changes with age, increasing from 1 m at the age of 1 year to 6 m at the age of 4 years, after which frequent pollarding limits the crown size to the growth of the poró between successive pollarding events. In Turrialba adult poró tree crowns reach 6 m between successive pollarding events. After each pollarding event, poró trees are dormant during the first month, without crown development. From the second month onwards, the crown of the poró tree develops rapidly so that 6 months after pollarding, the crowns have a spherical shape 6 m in diameter (Luján-Ferrer 1992; Nygren 1995; Russo 1984). Due to the short time interval between successive pollarding events, poró trees do not shed their leaves, retaining 100% of their foliage between consecutive pollarding events. Crown opacity was estimated at 0.65 using hemispheric photography (Luján-Ferrer 1992).

Laurel is a tree species native to the Latin American tropics and sub-tropics (Greaves and McCarter 1990), fast grower (Hummel 2000; Parresol and Devall 2013), with a commercial life cycle of

30 years in Turrialba's coffee plantations (Somarriba and Beer 1987; Somarriba et al. 2001). Laurel trees reach 30 m in total height (22 trunk height and 8 m crown height), 8 m crown diameter and 40 cm trunk diameter at breast height (dbh) in 20 years. Based on previous research, *C. alliodora* tree dimensions by age are presented in Table 2. Laurel trees lose foliage during the dry season, between February andApril, with 50% defoliation in February, 100% in March and April, and 50% in May. Between June and January, laurel trees have 100% of their foliage. Laurel canopy opacity is estimated at 0.45 (Andrade and Segura 2016).

Simulations

We simulated the monthly and annual patterns of shade on 1 ha of coffee plantation, in Turrialba (9° 53′ 28″ N, 83° 39′ 07″ W, 619 m altitude), on a flat terrain, with Y + axis oriented to the North. The simulation period was 20 years, between 09:00 and 15:00 h each day, and with 1-h time step (2555 simulation instants per year). This simulation took 6 min to run. Shade was accounted for at the height of the coffee plant in a central sampling area of 1368 m^2 to avoid edge effect. To illustrate the changes in shading with age, results are presented for ages 2, 8, and 12 years since crown dimensions of both poró and laurel stabilize at age 10 years.

Table 2 Diameter at breast height (dbh), trunk and crown height and crown diameter for *Cordia alliodora* in a coffee-based agroforestry system in Turrialba, Costa Rica. Adapted from Andrade and Segura (2016), Hummel (2000), Parresol and Devall (2013), Somarriba and Beer (1987), Somarriba et al. (2001)

Age	dbh	Height (m)			Crown diameter
		Trunk	Crown	Total	
1	4	1	2	3	2
2	8	1	2	3	4
3	12	3	3	6	5
4	15	5	4	9	6
5	18	8	5	13	6
6	21	9	6	15	7
7	24	11	6	17	7
8	26	13	7	20	7
9	28	15	7	22	7
10	30	17	8	25	8
11	31	18	8	26	8
12	32	19	8	27	8
13	33	20	8	28	8
14	34	20	8	28	8
15	35	20	8	28	8
16	36	20	8	28	8
17	37	20	8	28	8
18	38	20	8	28	8
19	39	20	8	28	8
20	40	20	8	28	8

Shade patterns

Canopy cover by shade trees increases with age, with maxima of 25% at age 2 and 60% at age 12 years (Fig. 2). Pollarding of the poró trees results in large variations in monthly canopy cover, with minima in January and July every year. This pattern has been documented by Luján-Ferrer (1992) using hemispherical photography. Laurel trees provide some canopy cover in January and July because their crowns are in full leaf in those months. The compensatory effect of laurel on monthly canopy cover increases with age (Fig. 3).

The average number of shade-hours per grid cell increases with age, from a minimum of 426 at age 2 to 1271 h-shade from age 12 onwards (Fig. 4). In term of percentages (out of a total, potential maximum of 2555 h-shade per year), shade levels in this agroforestry system amount to 17, 46 and 50% at age 2, 8 and 12, respectively.

Averages mask important variations in shade levels experienced by coffee plants planted at different locations under the trees, as depicted by the frequency distributions of the number of 1 m^2 grid cells experiencing different numbers of hours-shade (Fig. 5). Frequency distributions change with age. At age 2 years some grid cell experience 250 h-shade per year whereas the majority receives between 326 and 362 h-shade per year; at age 12 years some grid cells experience between 1054 and 1135 h-shade per year whereas the majority receives between 1216 and 1297 h-shade per year. The frequency of grid cells changes from bi-modal at age 2 years to a uni-modal frequency distribution at age 12 years (Fig. 5).

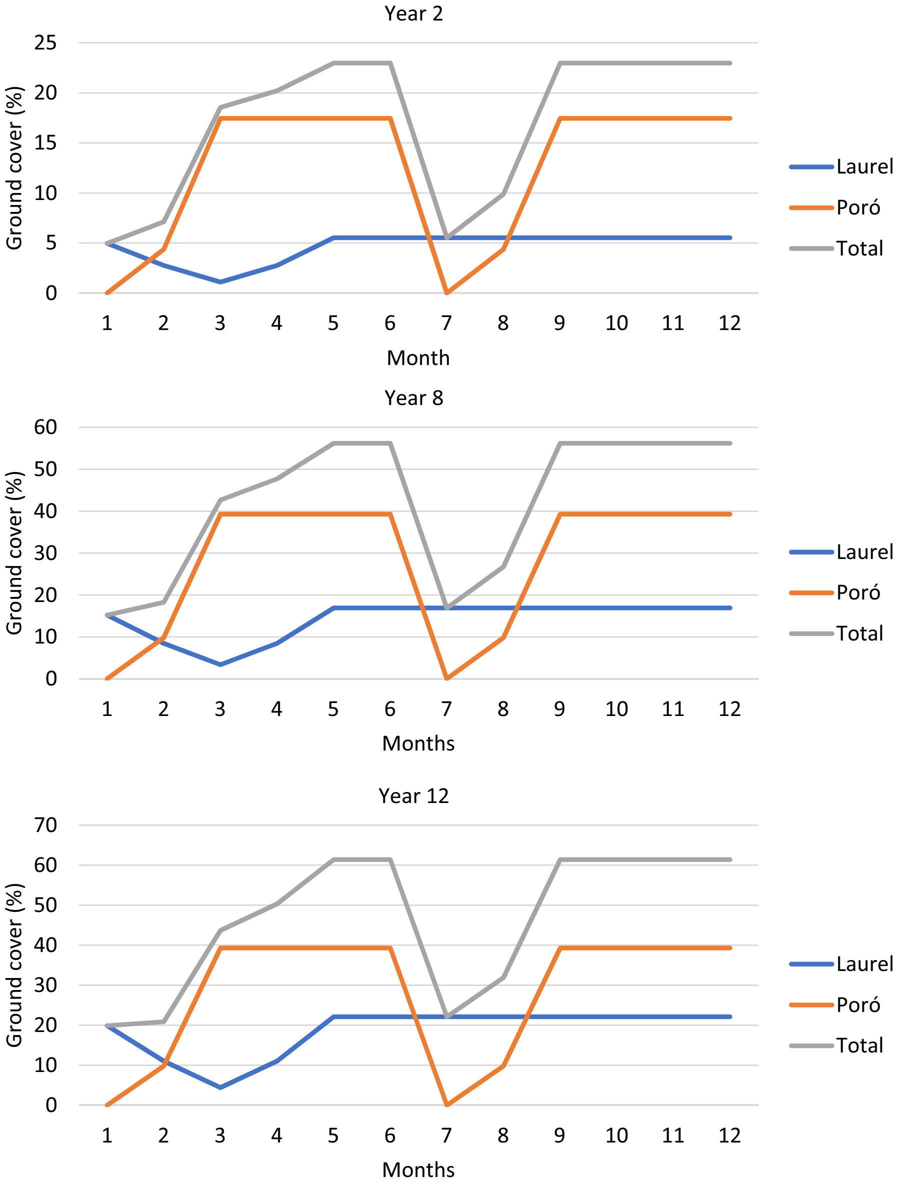


Fig. 3 Monthly ground cover and shade levels (total and by shade tree species) at ages 2, 8 and 12 years in a *Coffea arabica–Erythrina poeppigiana* (poró)–*Cordia alliodora* (laurel) agroforestry system in Turrialba, Costa Rica

Limitations and future improvements

Modeling the amount and spatial and temporal distribution patterns of solar radiation in the understory of tree canopies has been the subject of a vast amount of research, commensurate with its importance on forest regeneration and management, ecological processes, and on crop yields in agroforestry and other multiple cropping systems (Charbonnier et al. 2013; Leroy et al. 2009; Stadt and Lieffers 2000; Suarez-Salazar et al. 2018). Light transmission models for tree canopies span a wide range of approaches and levels of complexity, evolving from estimations using the Beer-Lambert law combined with leaf area indices (Sinoquet et al. 2007), to simple "big leaf" model for 1D, mono-layered, homogeneous canopies (Amthor 1994), to sun-shade models (de Pury and Farquhar 1997), to multi-layered, 3D, discontinuous tree canopies (Gu et al. 2022; Vincent and Harja 2002). ShadeMotion belongs to the later class of models.

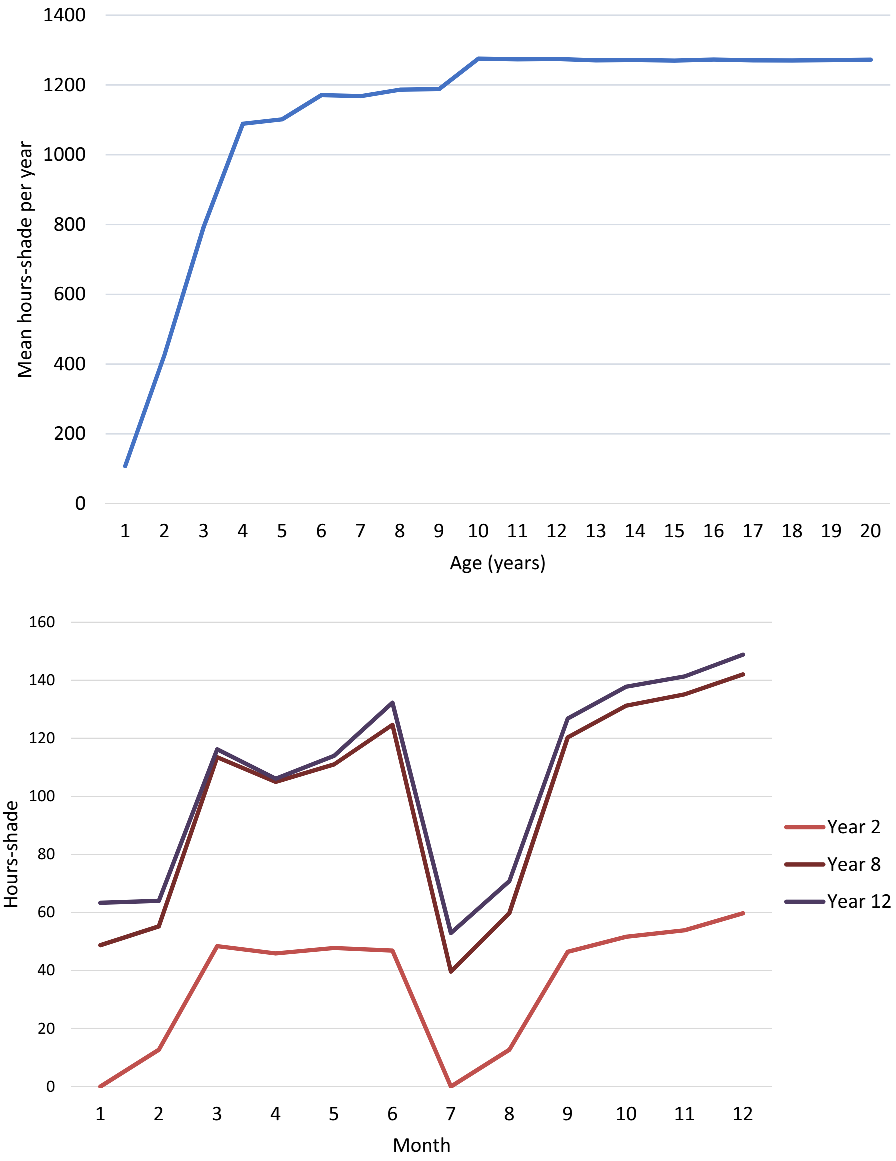


Fig. 4 Annual and monthly averages of the number of hours-shade in 1 m^2 grid cells at age 12 years in a *Coffea arabica–Erythrina poeppigiana–Cordia alliodora* agroforestry system in Turrialba, Costa Rica. Percentages refer to a maximum of 2555 simulation instants per year (from 09:00 to 15:00 h, 7 evaluations per day, for 365 days) and 210 simulation instants per month (7 evaluations per day, for 30 days)

The geometry, size and porosity of tree crowns, the cartesian coordinate position of trees on a plot, the deterministic nature of the position of the sun in the sky over the course of time, and tree leaf fall patterns used in ShadeMotion are common to other well-known physiological models of light interception by tree stands, such as MAESTRO (Norman and Jarvis 1975; Wang and Jarvis 1990) and its variants (Charbonnier et al. 2013) to models such as Yield-SAFE (Gidey et al. 2019), RATP (Sinoquet et al. 2002), WaNuLCAS (van Noordwijk and Lusiana 1999), MIXLIGHT (Stadt and Lieffers 2000), SExI-FS (Vincent and Harja 2008), and to many other models (Bartelink 1998; Brunner 1998; Canham et al. 1994; Pukkala et al. 1993; Ter-Mikaelian et al. 1997). All these models focus on the interception and utilization of solar radiation by leaves on a tree crown assuming different patterns of leaf inclination and 3D distribution within the crown. ShadeMotion focuses on modeling how tree crowns with varying degree of opacity and leaf fall patterns block solar radiation and shadow the ground or a crop canopy at certain height aboveground.

Most input variables used in ShadeMotion (tree and crown dimensions, leaf fall patterns, plot location, slopes and orientation, coordinate position of trees in the plot) can be measured cheaply, easily, and accurately. Excepting both crown shape and opacity. Estimations of crown transparency by eye, with hemispherical photography (Jonckheere et al. 2004), hand-held optical densitometers, or with LIDAR sensors are not exempted of estimation errors and biases. Numerous studies have assessed crown density in terms of leaf-area indexes (Weiss et al. 2004) and have explored the impacts of different leaf orientation, inclination angles, and leaf clustering in tree crowns on the accuracy of model predictions (Da Silva et al. 2011; Sampson and Smith 1993; Stadt and Leiffers 2000). These "fine grain" models provide accurate predictions of light interception but are highly demanding of data to estimate model parameters. ShadeMotion is a "coarse grain" model that assumes that leaves are randomly distributed both vertically and horizontally in a crown with a certain level of porosity. Correspondence between model predictions and field measurement has been shown to be highly sensitive to both crown foliage distribution (Stadt and Lieffers 2000; Wang and Jarvis 1990) and to asymmetric crown shapes (Cescatti 1997; Da Silva et al. 2011; Rautiainen et al. 2008). Using a simple crown density factor adjusted by monthly leaf phenology and uniform geometric shapes for tree crowns are the most sensitive elements of ShadeMotion and users are encouraged to make every effort to estimate both crown shape and opacity as accurately as possible. See for instance the SLIM software (Vincent and Harja 2002), combinations of leaf area indices measured with a plant canopy analyzer with detailed 3D models of plant architecture (Roupsard et al. 2008), and other methods (Lieffers et al. 1999).

At least three important improvements should be addressed in future versions of the software:

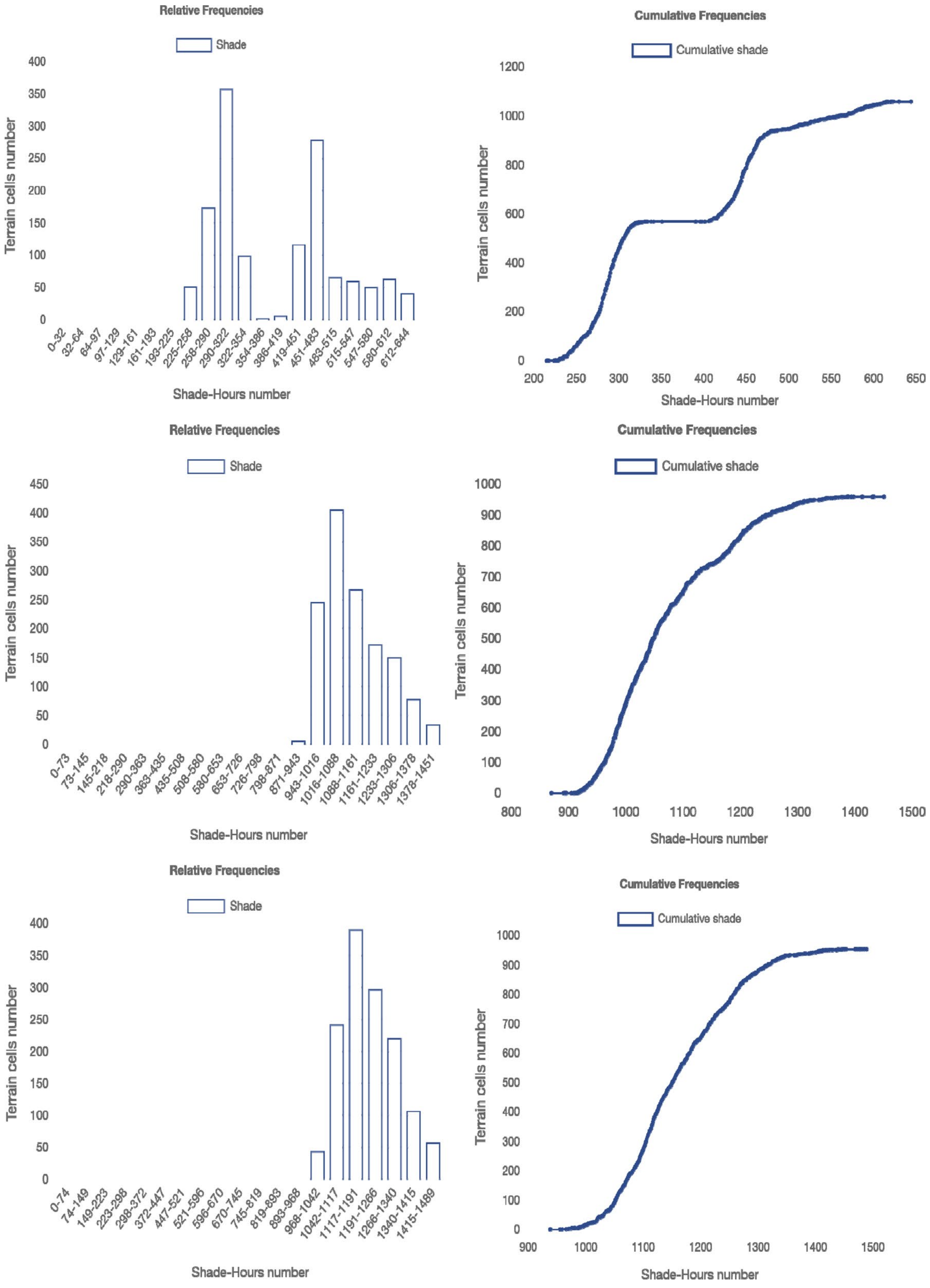
- Shadows cast by tree trunk and branches should be accounted for by representing trees as a cylindrical stem, with a low density, permanent branch structure, and a dynamic leaf canopy (the only element modeled in current version of the software). Tree trunks and permanent branches gain relevance in casting shade as trees get older (van Noordwijk and Ong 1999).
- Cloudiness patterns should be considered by adding, simple, user-defined functions describing the temporal pattern of the presence of clouds in the sky (e.g. sunny mornings and cloudy afternoons at given days, weeks or months in the year).
- Weekly (instead of monthly) leaf fall patterns should be incorporated in future versions of the software to more closely resemble the phenological pattern of a varied array of tree species.

The interactive manipulation of population density (thinning, mortality or harvest of trees), changing crown size by pollarding, and the possibility of calculating shade level at the height of a dynamic crop canopy in the understory are unique features of ShadeMotion. Field experimentation to evaluate how shading predictions match crop responses is warranted.

Conclusions

Striking an optimal balance between complexity and realism is a difficult task. ShadeMotion was developed as an applied, simple to parameterize and to use alternative to complex and input data demanding plant architectural and physiological models. But how close to reality (and applicability) are both kind of models is still an open question. The potential to realistically model tree management practices come with a tradeoff: users need to carefully study the tutorials and transit a learning curve to master the use of ShadeMotion. The development of a simpler, more intuitive, and user-friendly environment is warranted.

Estimated shade levels in the typical coffee-poró-laurel agroforestry system in Turrialba, Costa Rica are high, sometimes reaching up to 70% in mature coffee plantations. Monthly shading patterns show large variations in shade levels experienced by the coffee bushes. Tree growth, monthly leaf fall pattern in laurel, and pollarding of poró trees in January and July are responsible for the drastic changes in shade levels in this agroforestry system. This monthly pattern is coupled with the phenological pattern of the coffee plant, providing low shade levels during coffee flowering (January–February) and fruit ripening (July–August). However, high average shade levels may have significant, negative effects on coffee yields.


Relative Frequencies
Shade
Terrain cells number
400
350
300
250
200
150
100
50
0
0-32
32-64
64-97
97-129
129-161
161-193
193-225
225-258
258-290
290-322
322-354
354-386
386-419
419-451
451-483
483-515
515-547
547-580
580-612
612-644
Shade-Hours number
Cumulative Frequencies
Cumulative shade
Terrain cells number
1200
1000
800
600
400
200
0
200
250
300
350
400
450
500
550
600
650
Shade-Hours number
Relative Frequencies
Shade
Terrain cells number
450
400
350
300
250
200
150
100
50
0
0-73
73-145
145-218
218-290
290-363
363-435
435-508
508-580
580-653
653-726
726-798
798-871
871-943
943-1016
1016-1088
1088-1161
1161-1233
1233-1306
1306-1378
1378-1451
Shade-Hours number
Cumulative Frequencies
Cumulative shade
Terrain cells number
1000
900
800
700
600
500
400
300
200
100
0
800
900
1000
1100
1200
1300
1400
1500
Shade-Hours number
Relative Frequencies
Shade
Terrain cells number
400
350
300
250
200
150
100
50
0
0-74
74-149
149-223
223-298
298-372
372-447
447-521
521-596
596-670
670-745
745-819
819-893
893-968
968-1042
1042-1117
1117-1191
1191-1266
1266-1340
1340-1415
1415-1489
Shade-Hours number
Cumulative Frequencies
Cumulative shade
Terrain cells number
1000
900
800
700
600
500
400
300
200
100
0
900
1000
1100
1200
1300
1400
1500
Shade-Hours number

◂**Fig. 5** Relative and cumulative frequency distribution of the number of hours-shade in 1 m^2 grid cells (1368 m^2 sample area) at age 2, 8 and 12 years in a *Coffea arabica–Erythrina poeppigiana–Cordia alliodora* agroforestry system in Turrialba, Costa Rica

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Author contributions ES and FLS defined the scope for applications in agroforestry, RZ and JB developed and programmed the software, FQ developed the mathematics. ES detailed the coffee-based agroforestry system used as an example of the application of the software.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose, no competing interests, no proprietary interests in any material discussed in this article.

Appendix 1. Analytic expressions of tree crown shadows

Horizontal terrains

Following values are common to crown shapes in horizontal terrains.

$$X = (x - x_0)cos(Z) - (y - y_0)sen(Z)$$

$$Y = (x - x_0)sen(Z) + (y - y_0)cos(Z)$$

For crowns with system SRA located at the center of the crown: spheres and ellipses:

$$x_0 = x_a + (T + h - m)cotan(elev)sen(Z)$$

$$y_0 = y_a + (T + h - m)cotan(elev)cos(Z)$$

$$Z = azim + 180 - Y^+$$

For crowns with system SRA located at the base of the crown: semi-spheres, semi-ellipses, cones, inverted cones, cyllinders and umbrellas:

$$x_0 = x_a + (T - m)cotan(elev)sen(Z)$$

$$y_0 = y_a + (T - m)cotan(elev)cos(Z)$$

$$Z = azim + 180 - Y^+$$

With x_a, y_a being the Cartesian coordinates where the tree is planted in the terrain (SRU Cartesian coordinate System), azim is the suns azimuth, and Y^+ is the angle (clockwise) between the Y-axis and the north, a is half-diameter of the tree crown, H is the height of the crown, h is half crown height, and (x_0, y_0) are the Cartesian coordinates of the origin of the SRB reference system in SRU. A grid cell with coordinates X, Y is shaded by a tree crown if it satisfies at least one of the systems of inequalities describing a tree crown shadow.

Spheres

$$X^2 + (Y\ sen(elev))^2 \leq a^2$$

Ellipsoids

$$\frac{X^2}{a^2} + \frac{Y^2}{(h\ cotan(elev))^2 + a^2}$$

Semi-spheres

$$\begin{cases} X^2 + (Y\ sen(elev))^2 \leq a^2 \\ Y \geq 0 \end{cases}$$

$$X^2 + Y^2 \leq a^2$$

Semi-ellipsoids

$$\begin{cases} \frac{X^2}{a^2} + \frac{Y^2}{(H*cotan(elev))^2} \leq 1 \\ Y \geq 0 \end{cases}$$

$$X^2 + Y^2 \leq 0$$

Cones

$$\begin{cases} Y \leq \frac{H\ cotan(elev)}{a}X + H\ cotan(elev) \\ Y \leq -\frac{H\ cotan(elev)}{a}X + H\ cotan(elev) \\ Y \geq 0 \end{cases}$$

$$X^2 + Y^2 \leq a^2$$

Inverted cones

$$\begin{cases} Y \geq \frac{H\ cotan(elev)}{a} X \\ Y \geq -\frac{H\ cotan(elev)}{a} X \\ Y \leq H\ cotan(elev) \end{cases}$$

$$X^2 + (Y - H\ cotan(elev))^2 \leq a^2$$

Cylinders

$$\begin{cases} Y \leq H\ cotan(elev) \\ Y \geq 0 \\ X \leq a \\ X \geq -a \end{cases}$$

$$X^2 + Y^2 \leq a^2$$

$$X^2 + (Y - H\ cotan(elev))^2 \leq a^2$$

Umbrellas (cap of sphere)

An umbrella can be modeled by a flattened semi-ellipsoid that looks like a circle when viewed from above.

Tilted terrains

Inequalities presented for all crown shapes in horizontal terrains are valid in tilted terrains with the following modifications:

$$X = \left(x - x_0\right)cos(Z) - \left(y - y_0\right)sen(Z)cos(\sigma)$$

$$Y = \left(x - x_0\right)sen(Z) + \left(y - y_0\right)cos(Z)cos(\sigma)$$

For crowns with system SRA located at the center of the crown: spheres and ellipses:

$$x_0 = x_a + (T + h - m)cotan(elev)sen(Z)$$

$$y_0 = y_a + (T + h - m)cotan(elev)cos(Z)$$

$$Z = azim + 180 - \delta$$

For crowns with system SRA located at the base of the crown: semi-spheres, semi-ellipses, cones, inverted cones, cyllinders and umbrellas:

$$x_0 = x_a + (T + -m)cotan(elev)sen(Z)$$

$$y_0 = y_a + (T + -m)cotan(elev)cos(Z)$$

$$Z = azim + 180 - \delta$$

where σ is the angle of maximum slope of the terrain and δ the angle of orientation of the positive Y^+ axis, which is aligned along the maximum slope of the terrain.

References

Amthor JS (1994) Scaling CO_2-photosynthesis relationships from the leaf to the canopy. Photosynthesis and global changes in the environment. Photosynth Res 39:321–350

Andrade HJ, Segura MA (2016) Dinámica de la sombra de *Cordia alliodora* en sistemas agroforestales con café en Tolima, Colombia. Agron Costarric 40(2):77–86

Bartelink HH (1998) Radiation interception by forest trees: a simulation study on effects of stand density and foliage clustering on absorption and transmission. Ecol Model 105:213–225

Brunner A (1998) A light model for spatially explicit forest stand models. For Ecol Manag 107:19–46

Canham CD, Finzi AC, Pacala SW, Burbank DH (1994) Causes and consequences of resource heterogeneity in forests: interspecific variation in light transmission by canopy trees. Can J For Res 24:337–349

Cerda R, Deheuvels O, Calvache D, Niehaus L, Saenz Y, Kent J, Vilchez S, Villota A, Martinez C, Somarriba E (2014) Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agrofor Syst 88:957–981. https://doi.org/10.1007/s10457-014-9691-8

Cescatti A (1997) Modelling the radiative transfer in discontinuous canopies of asymmetric crowns.1. Model structure and algorithms. Ecol Model 101:263–274

Charbonnier F, le Maire G, Dreyer E, Casanoves F, Christina M, Dauzat J, Eitel JUH, Vaast P, Vierling LA, Roupsard O (2013) Competition for light in heterogeneous canopies: application of MAESTRA to a coffee (*Coffea arabica* L.) agroforestry system. Agric For Meteorol 181:152–169

Côté JF, Fournier RA, Egli R (2011) An architectural model of trees to estimate forest structural attributes using terrestrial LiDAR. Environ Model Softw 26(6):761–777. https://doi.org/10.1016/j.envsoft.2010.12.008

Da Silva D, Balandier P, Boudon F, Marquier A, Godin C (2011) Modeling of light transmission under heterogeneous forest canopy: an appraisal of the effect of the precision level of crown description. Ann For Sci. https://doi.org/10.1007/s13595-011-0139-2

de Pury DGG, Farquhar GD (1997) Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models. Plant Cell Environ 20:537–557

Dupraz C, Wolz KJ, Lecomte I, Talbot G, Vincent G, Mulia R, Bussière F, Ozier-Lafontaine H, Andrianarisoa S, Jackson N, Lawson G, Dones N, Sinoquet H, Lusiana B, Harja D, Domenicano S, Reyes F, Gosme M, Van Noordwijk M (2019) Hi-sAFe: a 3D agroforestry model for integrating dynamic tree–crop interactions. Sustainability 11(8):2293. https://doi.org/10.3390/su11082293

Englund SR, O'Brien JJ, Clark DB (2000) Evaluation of digital and film hemispherical photography and spherical densiometry for measuring forest light environments. Can J For Res 30:1999–2005

Fiala ACS, Steven L, Garman SL, Gray AN (2006) Comparison of five canopy cover estimation techniques in the western Oregon Cascade Forest. Ecol Manag 232:188–197

Frazer GW, Fournier RA, Trofymow JA, Hall RJ (2001) A comparison of digital and film fisheye photography for analysis of forest canopy structure and gap light transmission. Agric For Meteorol 109:249–263

Gidey T, Oliveira TS, Crous-Duran J, Palma JHN (2019) Using the yield-SAFE model to assess the impacts of climate change on yield of coffee (*Coffea arabica* L.) under agroforestry and monoculture systems. Agrofor Syst 94(1):57–70. https://doi.org/10.1007/s10457-019-00369-5

Gidoin C, Avelino J, Deheuvels O, Cilas C, Ngo Bieng MA (2014) Shade tree spatial structure and pod production explain frosty pod rot intensity in cacao agroforests, Costa Rica. Phytopathology 104(3):275–281. https://doi.org/10.1094/PHYTO-07-13-0216-R

Greaves A, McCarter PS (1990) *Cordia alliodora* A promising tree for tropical agroforestry. Oxford Forestry Institute, University of Oxford, Tropial Forestry Papers No. 22, Oxford, UK. 37

Gren L, Antinyan V (2017) On the relation between unit testing and code quality. In: Euromicro conference on software engineering and advanced applications (SEAA2017), Vienna, Austria. https://doi.org/10.1109/SEAA.2017.36

Grimm V, Railsback SF, Vincenot CE, Berger U, Gallagher C, DeAngelis DL, Edmonds B, Ge J, Giske J, Groeneveld J, Johnston AS (2020) The ODD protocol for describing agent-based and other simulation models: a second update to improve clarity, replication, and structural realism. J Artif Soc Soc Simul 23(2):7. https://doi.org/10.18564/jasss.4259

Gu S, Wen W, Xu T, Lu X, Yu Z, Guo X, Zhao C (2022) Use of 3D modeling to refine predictions of canopy light utilization: a comparative study on canopy photosynthesis models with different dimensions. Front Plant Sci 13:735981. https://doi.org/10.3389/fpls.2022.735981

Guevara-Escobar A, Tellez J, Gonzalez-Sosa E (2005) Use of digital photography for analysis of canopy closure. Agrofor Syst 65:175–185

Hanan J (1997) Virtual plants—integrating architectural and physiological models. Environ Model Softw 12(1):35–42. https://doi.org/10.1016/S1364-8152(96)00040-0

Hilker T, Leeuwen M, Coops NC, Wulder MA, Newnham GJ, Jupp DL, Culvenor DS (2010) Comparing canopy metrics derived from terrestrial and airborne laser scanning in a Douglas-fir dominated forest stand. Trees 24:819–832

Hummel S (2000) Height, diameter and crown dimensions of *Cordia alliodora* associated with tree density. For Ecol Manag 127:31–40

Jonckheere I, Fleck S, Nackaerts K, Muys B, Coppin P, Weiss M, Baret F (2004) Review of methods for in situ leaf area index determination. Part I. Theories, sensors and hemispherical photography. Agric For Meteorol 121(1/2):19–35

Kato A, Moskal LM, Schiess P, Swanson ME, Calhoun D, Stuetzle W (2009) Capturing tree crown formation through implicit surface reconstruction using airborne lidar data. Remote Sens Environ 113:1148–1162

Korhonen L, Korhonen KT, Rautiainen M, Stenberg P (2006) Estimation of forest canopy cover: a comparison of field measurement techniques. Silva Fenn 40(4):577–588

Kuuluvainen T, Pukkula T (1987) Effect of crown shape and tree distribution on the spatial distribution of shade. Agric For Meteorol 40:215–231

Läderach P, Ramirez-Villegas J, Navarro-Racines C et al (2017) Climate change adaptation of coffee production in space and time. Clim Change 141:47–62. https://doi.org/10.1007/s10584-016-1788-9

Lamanda N, Dauzat J, Jourdan C, Martin P, Malezieux E (2008) Using 3D architectural models to assess light availability and root bulkiness in coconut agroforestry systems. Agrofor Syst 72:63–74. https://doi.org/10.1007/s10457-007-9068-3

Leroy C, Sabatier S, Sari N, Wahyuni S, Barczi J, Dauzat J, Laurans M, Auclair D (2009) Virtual trees and light capture: a method for optimizing agroforestry stand design. Agrofor Syst 77:37–47

Lieffers VJ, Messier C, Stadt KJ, Gendron F, Corneau PG (1999) Predicting and managing light in the understory of boreal forests. Can J For Res 29(6):796–811

Llanderal T (1998) Diversidad del dosel de sombra en cafetales de Turrialba, Costa Rica. Thesis Mag. Sci., CATIE, Turrialba, Costa Rica, p 59

Luján-Ferrer R (1992) Dinámica de doseles de tres especies de leguminosas de sombra y efectos sobre la fenología de seis cruces interclonales de cacao. Thesis Mag. Sci., CATIE, Turrialba, Costa Rica, p 101

McPherson EG, Rowntree RA (1988) Geometric solids for simulation of tree crowns. Landsc Urban Plan 15:79–83

Mialet-Serra I, Dauzat J, Auclair D (2001) Using plant architectural models for estimation of radiation transfer in a coconut-based agroforestry system. Agrofor Syst 53:141–149

Norman JM, Jarvis PG (1975) Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.). V. Radiation penetration theory and a test case. J Appl Ecol 9:747–766

Nygren P (1995) Carbon and nitrogen dynamics in *Erythrina poeppigiana* (Leguminosae: phaseoleae) trees managed by periodic prunings. PhD Dissertation, University of Helsinki, Helsinki, Finland, p 61

Orozco-Aguilar L, López-Sampson A, Leandro ME, Robiglio V, Reyes M, Bordeaux M, Sepulveda N, Somarriba E (2021) Elucidating pathways and discourses linking cocoa cultivation to deforestation, reforestation and tree cover change in Nicaragua and Peru. Front Sustain Food Syst. https://doi.org/10.3389/fsufs.2021.635779

Parresol BR, Devall MS (2013) Patterns of diametric growth in stem-analyzed laurel trees (*Cordia alliodora*) in a Panamanian forest. Southwest Nat 58(2):170–178

Pinoargote M, Cerda R, Mercado L, Aguilar A, Barrios M, Somarriba E (2017) Carbon stocks, net cash flow and family benefits from four small coffee plantation types in Nicaragua. For Trees Livelihoods 26(3):183–198. https://doi.org/10.1080/14728028.2016.1268544

Pukkala T, Kuuluvainen T, Stenberg P (1993) Below-canopy distribution of photosynthetically active radiation and its relation to seedling growth in a boreal *Pinus sylvestris* stand: a simulation approach. Scand J For Res 8:313–325

Quesada-Chaverri F (2021) Derivación de las fórmulas de sombras de árboles empleadas en el programa ShadeMotion. Serie Técnica Manual Técnico 151, CATIE, Turrialba, Costa Rica, p 35. http://hdl.handle.net/11554/11358

Rautiainen M, Mõttus M, Stenberg P, Ervasti S (2008) Crown envelope shape measurements and models. Silva Fenn 42(1):19–33

Reddy PR, Amarnadh V, Bhaskar M (2012) Evaluation of stopping criterion in contour tracing algorithms. Int J Comput Sci Inform Technol 3(3):3888–3894

Roupsard O, Dauzat J, Nouvellon Y, Deveau A, Feintrenie L, Saint- André L, Mialet-Serra I, Braconnier S, Bonnefond JM, Berbigier P, Epron D, Jourdan C, Navarro M, Bouillet JP (2008) Cross-validating Sun-shade and 3D models of light absorption by a tree-crop canopy. Agric For Meteorolgy 148:549–564

Russo RO (1984) Studies on *Erythrina poeppigiana* (Walpers) O.F. Cook, a versatile tree in Costa Rican farms. PhD Dissertation, Southeastern University, New Orleans, Louisiana, USA, p 131

Sampson DA, Smith FW (1993) Influence of canopy architecture on light penetration in lodgepole pine (*Pinus contorta* var. latifolia) forests. Agric For Meteorol 64:63–79

Seidel D, Fleck S, Leuschner C (2012) Analyzing forest canopies with ground-based laser scanning: a comparison with hemispherical photography. Agric For Meteorol 154–155:1–8

Sellers WD (1965) Physical climatology. Chicago University Press, Chicago, p 272

Sharma P, Diwakar M, Lal N (2013) Edge detection using moore neighborhood. Int J Comput Appl 61(3):26–30

Silva C, Orozco L, Rayment M, Somarriba E (2013) Conocimiento local sobre los atributos deseables de los árboles y el manejo del dosel de sombra en los cacaotales de Waslala, Nicaragua. Agrofor Am 49:51–60

Sinoquet H, Le Roux X, Adam B, Ameglio T, Daudet FA (2002) RATP: a model for simulating the spatial distribution of radiation absorption, transpiration and photosynthesis within canopies: application to an isolated tree crown. Plant Cell Environ 24:395–406

Sinoquet H, Stephan J, Sonohat G, Lauri PE, Monney Ph (2007) Simple equations to estimate light interception by isolated trees from canopy structure features: assessment with three-dimensional digitized apple trees. New Phytol 175:94–106

Somarriba E, Beer J (1987) Dimensions, volumes, and growth of *Cordia alliodora* in agroforestry systems. For Ecol Manag 18:113–126

Somarriba E, Valdivieso R, Vásquez W, Galloway G (2001) Survival, growth, timber productivity and site index of *Cordia alliodora* in forestry and agroforestry systems. Agrofor Syst 51:111–118

Somarriba E, Zamora R, González J, Malek M, Vargas E, Sinclair F, Quesada F (2020) ShadeMotion: the análisis of tree shade patterns. Tutorial. CATIE, Serie técnica. Manual técnico 145, CATIE, Turrialba, Costa Rica, p 50. www.shademotion.net

Stadt KJ, Lieffers VJ (2000) MIXLIGHT: a flexible light transmission model for mixed-species forest stands. Agric For Meteorol 102:235–252

Suárez Salazar JC, Ngo Bieng MA, Melgarejo LM, Di Rienzo JA, Casanoves F (2018) First typology of cacao (*Theobroma cacao* L.) systems in Colombian Amazonia, based on tree species richness, canopy structure and light availability. PLoS ONE 13(2):e0191003

Ter-Mikaelian MT, Wagner RG, Shropshire C, Bell FW, Swanton CJ (1997) Using a mechanistic model to evaluate sampling designs for light transmission through forest canopies. Can J For Res 27:117–126

Van Noordwijk M, Lusiana B (1999) WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agrofor Syst 43:217–242

Van Noordwijk M, Ong CK (1999) Can the ecosystem mimic hypotheses be applied to farms in African savannhas? Agrofor Syst 45(1):131–158

Vezy R, le Maire G, Christina M, Georgiou S, Imbach P, Hidalgo HG, Alfaro EJ, Blitz-Frayret C, Charbonnier F, Lehner P, Loustau D, Roupsard O (2020) DynACof: a process-based model to study growth, yield and ecosystem services of coffee agroforestry systems. Environ Model Softw 124:104609. https://doi.org/10.1016/j.envsoft.2019.104609

Vincent G, Harja D (2002) SLIM software: a simple light interception model for multi-species, multi-strata forests. Bois For Trop 272(2):97–100

Vincent G, Harja D (2008) Exploring ecological significance of tree crown plasticity through three-dimensional modelling. Ann Bot 101:1221–1231

Wang YP, Jarvis PG (1990) Description and validation of an array model—MAESTRO. Agric For Meteorol 51:257–280

Weiss M, Baret F, Smith GJ, Jonckheere I, Coppin P (2004) Review of methods for in situ leaf area index (LAI) determination. Agric For Meteorol 121(1–2):37–53. https://doi.org/10.1016/j.agrformet.2003.08.001