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Preliminary modeling of light availability in a diverse agroforestry system using a spatially explicit forest simulator

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ABSTRACT

Researchers theorize there is a particular spacing within and between rows that maximizes light capture given size, shape, and opacity of woody species in diverse agroforestry systems (DAS). Studies of these mixed perennial cropping systems have failed to analyze this optimum spacing quantitatively. This study attempts to address this issue through the following aims: (1) determine optimal layouts for light capture, (2) calculate percentage of light received by species at different layout densities, and (3) better understand differences in light availability at plant and plot scales. This study modeled four University of Illinois DAS research treatments ranging from one to three species within a tree row. The spatially explicit forest simulator, SORTIE-ND, was used to analyze the light availability, referred to as global light index (GLI), at treatment maturity on a 1-m^2 basis across the field site. Results reveal that GLI is lowest when species spacing is decreased and canopy levels do not overlap. On a plot scale, treatments containing tree rows with multiple canopy levels of distinctly separate heights allowed for maximum GLI while tree rows with only a single species had the lowest. On a plant scale, the tallest trees received near full light as long as canopies did not overlap. Understory shrubs received little to no light when density and number of tree canopies increased. Adjusting the density and number of canopy levels in DAS has significant effects on GLI, but should be further studied using additional treatments to identify quantitative optimum.

INTRODUCTION

Plant growth is determined by the most limiting factor. When the limiting factor is not water or nutrients, it is most often light (Monteith et al. 1991; Monteith 1994). The conversion efficiency of photosynthetically active radiation (PAR, 400-700 nm wavelength radiation) determines plant net primary productivity (Monteith 1972; Cannel et al. 1996). This is especially important in agroforestry systems, which combine woody species with annuals to create multiple canopy layers. Light availability varies considerably across these systems in comparison to uniform corn and soybean monocultures (Luedeling et al. 2014). Multi-story, diverse agroforestry systems (DAS) often lead to unintended spatial differences in solar capture across a field site that affects growth and production (Rivest et al. 2009; Reynolds et al. 2007; Muthuri et al. 2009).

Understanding how to control for spatial differences and design a system to maximize light capture has been shown to increase the overall production of agroforests (Dupraz 2004). Maximizing light capture will require a different layout for each site due to differences in climate, economics, and manager preferences

(Nuberg et al. 2009). Studying a field site *in situ* is a practical method to understand what species and spacing works best in an area. This is not practical though for many farmers and researchers working on shorter time scales. Agroforestry models offer an alternative to this problem by allowing insight into the dynamics of a site at maturity before it is planted.

To date, agroforestry models have been poor predictors of light availability, especially in multi–story polycultures. The majority of models are either spatially explicit, but oversimplified or complex, but not spatially explicit (Malézieux 2009). Both problems pose major difficulties when attempting to utilize a model for systems with multiple stories and multiple crops in a single row. A basic approach to begin to address this problem is needed.

Here, we propose a method of analyzing solar capture of various DAS layouts using a simple modeling approach. Model selection was done following criteria and model comparisons laid out by Malézieux et al. (2009). SORTIE-ND, a simple, yet powerful model formed by Pacala et al. (1993), was selected for this research. It has been used extensively in exploring light dynamics of forestry systems, especially understory light (Canham et al. 1999). This model is both spatially explicit and focused on individual trees (Brunner 1998). The model applies to DAS because it can handle individually based multi-story modeling of light dynamics using a small set of parameters, making it relatively simple (Astrup 2006).

SORTIE-ND will explore differences in light conditions at the Multifunctional Woody Polyculture (MWP) research site at the University of Illinois at Urbana-Champaign (UIUC). The MWP is a 30-acre multi-story intercropping agroforest that attempts to investigate the above and belowground interactions of mixed woody perennial species on a plant, system, and commercial scale. The site contains seven treatments, replicated four times. Treatments represent a broad range from monoculture woody crops to a diverse multistory crop system. The woody species include Chinese chestnut, European hazelnut, apple, and black currant. Planted in May 2015, the site will not yield detailed data on light interactions for many years to come. This makes it an ideal candidate for use within SORTIE-ND to explore various light dynamics questions.

In this paper, a spatially explicit model is used to discern the differences in light capture between various DAS inter-cropping layouts at the MWP research site. The aims of the study were to (1) determine the optimal layout for light capture, (2) calculate the percentage of light each species is receiving to compare between treatments, and (3) better understand differences in light availability at plant and plot scales to help guide management decisions. This preliminary approach to modeling light transmission attempts to progress the research on optimization models for DAS.

MATERIALS AND METHODS

Study Site and Species

The MWP study site is located in Urbana, IL, U.S.A (Latitude: 40.07913). Established on the UIUC campus in May 2015, it consists of seven treatments plots (80-m x 80-m) each replicated four times. Treatments 1, 2, and 7 do not fit the scope of this study and are excluded. Treatments 3-6 were modeled to test differences among incremental increases in complexity of similar intercropping organizations. They each contain two, three or four of the following species: *Malus domestica L.* (apple), *Catanea mollisima* (Chinese chestnut), *Ribes nigrum L.* (black currant), and *Corylus avellana L.* (hazelnut). The treatments consist of two row layouts. Row A consists of chestnut trees. Row B contains hazelnut trees. In some treatments, rows A and B have currants and/or apples in between the chestnuts/hazelnuts. Trees are spaced evenly within row. Rows are spaced 9.1-m apart. If present, currants are evenly spaced every 0.91-m within the row between trees. See Table 1 for further descriptions and spacing of the treatments.

Table 1. MWP treatments 3-6 layout and species

Treatment	Row Layout	Tree Species Present			Black Currants	Within-Row Tree Spacing
		Chestnut	Hazelnut	Apple		
3	A	X				9.1-m
	B		X			4.57-m
4	A	X			X	9.1-m
	B		X		X	4.57-m
5	A	X			X	4.57-m
	B		X		X	2.29-m
6	A	X		X	X	4.57-m
	B		X	X	X	2.29-m

* Rows are spaced 9.1-m apart and alternate between layout A and B
** Apple trees alternate with chestnut/hazelnut within rows of treatment 6
*** Currants are evenly spaced every 0.91-m between trees

SORTIE-ND Information

The SORTIE-Neighborhood Dynamics (SORTIE-ND) forest simulator was chosen to model light transmission of the MWP research site. SORTIE was initially developed to simulate forest regeneration after small disturbances in the hardwood forests of Northeastern U.S (Canham et al. 1994; Pacala et al. 1996). This model is individually based and spatially explicit, allowing tree species to have specific characteristics and be analyzed individually. It contains many different submodels, including the light sub-model that determines light interactions at the neighborhood scale.

The light submodel within SORTIE predicts incident radiation at any given location within a forest as a function of (1) species-specific light transmission coefficients, 2) variation in crown geometry as a function of tree size, (3) the identities, sizes, and spacing of trees in the immediate neighborhood, and (4) the local sky brightness distribution (Pacala et al. 1993). The power of the light model is largely a function of the simplicity of the input required for accurate predictions of spatial variation in understory light levels (Canham et al. 1999 and sources within). This allows it to be easily adapted to fit the needs of modeling light dynamics within the MWP.

For more information on the details of the SORTIE-ND model, refer to the SORTIE-ND User Manual.

Crown Allometry

Three functions determine the structure of trees in SORTIE-ND:

1. Tree height as a function of diameter at breast height (DBH)
2. Crown radius as a function of DBH
3. Crown depth as a function of tree height

These functions are used to determine the geometry of trees in the model that are necessary when analyzing forests that contain trees of many ages and sizes (Beaudet et al. 2002). However, this study is focused on a managed, DAS with identical cultivars. The mature tree allometry will theoretically be identical for each individual species across the MWP layouts. Therefore tree height, canopy radius, and canopy height variables are constant in the model. Tree height is defined within the tree map used for analysis. Crown radius and height are defined by the following equations:

Crown Radius = C1 * DBH^{a}
Crown Height = C2 * height^{a}
where:

- **Crown radius**: in meters
- **Crown height:** the distance from the top to the bottom of the crown cylinder, in meters
- **C1:** Slope of asymptotic crown radius parameter
- **C2:** Slope of asymptotic crown height parameter
- **DBH:** in cm
- **Height:** Tree's height in cm
- **a:** Crown radius exponent parameter
- **b:** Crown height exponent parameter

The sources of the specific species data parameters are noted in Table 2.

Light Behaviors

Global Light Index (GLI) is the percentage of full sun received at a point in the plot. GLI values range from 0 (no sun) to 100 (full sun). There are two light behaviors in SORTIE that utilize GLI for data analysis: GLI Map Creator and GLI Light. The geometry of the trees, their spacing, and species-specific light transmission (amount of light transmitted through the canopy) forms the basis of the models.

Table 2. Species allometry data used for the light model

	Apple	Chestnut	Currant	Hazelnut
DBH (cm)	[a] 11.28	[c] 20.96	[d] 1.5	[f] 9.9
Canopy Height (m)	[a] 3.5	[c] 5.72	[d] 1.25	[f] 2.8
Canopy Radius (m)	[a] 1.85	[c] 3.23	[d] 0.558	[f] 1.65
Crown Height (m)	[a] 2.5	[c] 3.69	[d] 1.24	[f] 2.0
Light Trans.	[b] 0.163	[c] 0.071	[e] 0.05	[g] 0.09
C1 (radius)	0.164	0.154	0.3	0.167
C2 (height)	0.714	0.645	0.992	0.714

a. Auto *et al.* 2011
b. Photos taken at UIUC apple orchards
c. Data & photos collected from 8-yr Qing chestnuts at the Center for Agroforestry at the University of Missouri
d. Averages from NDSU (2013) report.
e. Photos taken at Woody Perennial Polyculture Research Site at UIUC
f. McCluskey *et al.* 2009
g. Photos taken from Oregon State University hybrid hazelnut trees provided on web

Species-Specific Crown Openness

Species-specific crown opacity was determined following methods laid out in Canham et al. (1994). Canopy photographs were taken at 45^{o} angles around the tree, then analyzed using the software CAN-EYE to determine light transmission in a canopy (CAN-EYE version 6.312 2013). The average canopy transmission from all angles was then calculated and compiled in Table 2 under "light transmission."

GLI Map Creator (Plot Scale)

This behavior calculates the GLI value for each cell in the grid object, which is the treatment plot in this study. Users set the height at which this value is calculated. A GLI map was created for the heights (in meters) at ground level (0.01m) and above the currant, hazelnut, and apple canopies (currant: 1.26; hazelnut: 2.81; apple: 3.51). Chestnut canopies are not included in analysis because they are the tallest tree species in the study and always have full light at their crown. A value is calculated every 1-m^{2} to identify fine differences in light availability at the scale of the smallest plant species (black currant). The model software requires treatment layouts to be greater than 100-m x 100-m. Since the true treatment plots are only 80-m x 80-m, they were extended in length and width to fit the required size.

GLI Light (Plant Scale)

This behavior derives GLI values for individual trees of each species. It gives a more precise measure of the light availability of each tree species.

Data Analysis

R 3.2.1 was used to analyze statistical differences between GLI levels of each treatment (R Development Core Team 2013).

RESULTS

Plot Level

The data were non-normal and therefore were analyzed using a non-parametric one-way ANOVA on ranks. The GLI levels on a square meter level between treatments 3 through 6 were significantly different (Kruskal-Wallis; p<2e-16) (Table 3). All treatments significantly differed in GLI (Post-hoc Dunn test; all p<2e-16).

Table 3. Summary statistics of treatment GLI plots

Treatment	3	4	5	6
Mean	54.35	49.36	36.45	40.94
Median	61	58	43	48
Minimum	7	0	0	0
Maximum	88	88	87	87

Exploratory analysis of differences in GLI measured on the ground, at the top of the currant canopy, and at the top of the hazelnut canopy show that GLI is lowest nearest the ground, and when plots have the greater density (Figure 1).

Treatment 5, consisting of chestnuts, hazelnuts, and currants, has the lowest light availability (36.45%) of all treatments, while treatment 3 has the highest (54.35%) (Table 3). Relative comparisons between plots show that the more species and canopies a treatment has, the more light it can intercept (Table 4). Alternating single species rows of chestnuts and hazelnuts (such as in treatment 4) reveal high levels of light availability in the alley.

Canopy Light Capture Percent Differences Between Treatments					
		Comparison Treatment			
		3	4	5	6
Treatment	3		-10.02	-48.53	-32.38
	4	11.06		-35.01	-20.33
	5	39.69	25.93		10.87
	6	29.72	16.90	-12.20	

Table 4. Relative differences in light capture between

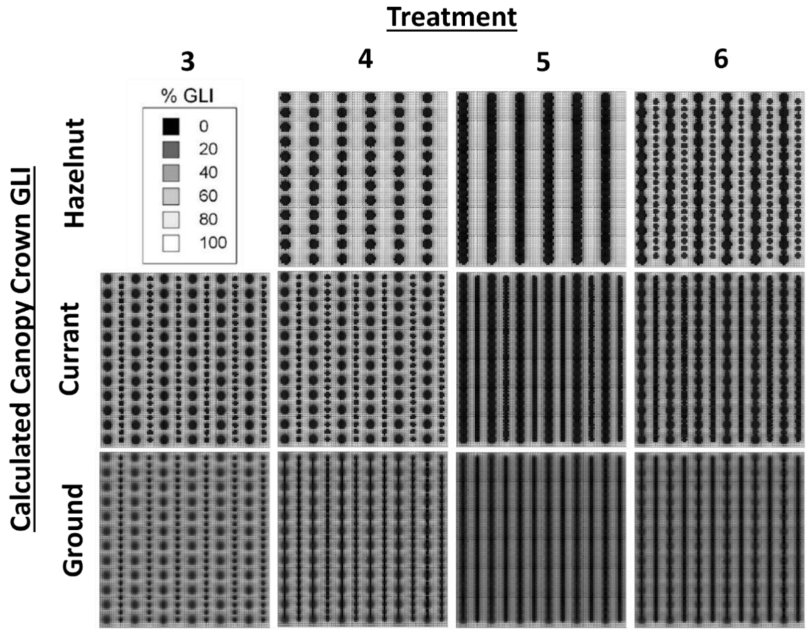

Figure 1. GLI map creator output visualization of each treatment. The GLI for each map is calculated at different canopy crowns

The GLI levels drop on average per cell when the spacing between trees becomes denser and when more canopy layers are added. As expected, the more trees occupying the space, the more light is being captured. This is seen in the average GLI between treatment 3 and 4 when an additional canopy layer is added, and between 4 and 5 when the trees become denser (Table 4).

Including more canopy layers resulted in a more uniform distribution of light on the canopy floor (Figure 2). Treatment 6 has the most uniform light distribution relative to the other treatments.

Plant Level

In addition to modeling entire plots, the light model runs predictions on the GLI level per plant at mid-crown (Table 5). Chestnuts (the tallest tree) have the greatest GLI, receiving full sunlight in every treatment. In treatment 6, apples have the second highest GLI (~80%). In treatments 3 and 4, hazelnuts capture full sunlight, but when the density is doubled in treatments 5 and 6 it drops to 50-70%.

Currants, as the shrub layer, receive the least sunlight in the model. They have a broad range of GLI values in treatment 4 ranging from near 0% to 50% depending on the proximity to the chestnut tree. The GLI for currants drops to near zero in treatments 5 and 6 where the density of plants is doubled.

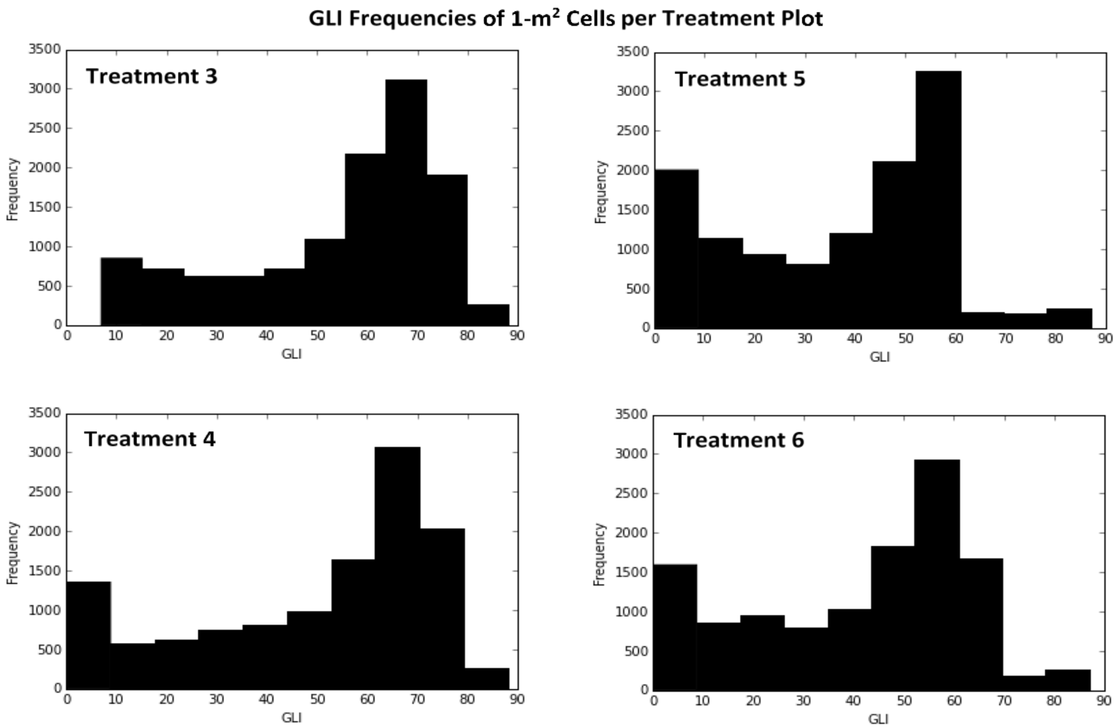

Figure 2. Model estimates of GLI frequencies in treatments

Treatment	Species	Mid-Crown GLI (# of individuals)									
		0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
3	**Chestnut**	0	0	0	0	0	0	0	0	0	38
	Hazelnut	0	0	0	0	0	0	0	0	0	73
4	**Chestnut**	0	0	0	0	0	0	0	0	0	38
	Hazelnut	0	0	0	0	0	0	0	0	0	73
	Currant	450	35	35	10	102	105	0	0	0	0
5	**Chestnut**	0	0	0	0	0	0	0	0	67	6
	Hazelnut	0	0	0	0	0	0	0	137	6	0
	Currant	631	0	0	0	0	0	0	0	0	0
6	**Apple**	0	0	0	0	0	0	0	35	0	70
	Chestnut	0	0	0	0	0	0	0	0	0	38
	Hazelnut	0	0	0	0	0	67	3	0	3	0
	Currant	593	38	0	0	0	0	0	0	0	0

Table 5. Model output GLI at mid-crown of each plant per treatment block. (Plant counts are relative, and not exact to true plant counts of plot)

DISCUSSION

Management Implications: Plot Scale

The addition of a tree canopy and more closely spaced trees (comparing treatment 3 to 5) can capture nearly 40% more light than alternating rows of hazelnuts and chestnuts only (Table 4). Light is the driver of photosynthesis and in turn plant growth. The ability to capture more light means the plants will be able to improve their growth and/or crop yields, assuming light is the limiting factor. Treatment 5 has the highest light capture of all treatments and should be the most productive followed by treatment 6, 4, and 3 respectively. However, this assumes there is a direct relationship between plant growth and crop yield, which is not true. Predicting accurate fruit/nut yields will require annual data to form a site-specific statistical model (Jiménez 2003). Further research would be needed to correlate agroforestry designs directly with final tree crop production.

Maximizing light capture should not focus only within tree rows. The alleys between tree rows receive high levels of sunlight and should be considered for cultivation, especially in the first few years of growth. The majority of cells in the treatments 3 and 4 alley have a GLI greater than 70 at maturity. This represents opportunity land for farmers to plant additional crops such as corn or soybean that need high levels of sunlight. Having fast growing annuals in the tree alleys represent financial opportunities for farmers looking to further diversify.

Management Implications: Plant Scale

Having adequate separation of each canopy level in a multi-story agroforestry system may allow for improved light capture. Hazelnuts change from 70% GLI in treatment 5 to a 50% GLI in treatment 6 where apple trees are added. Apple trees and hazelnut trees share relatively similar canopy heights. This suggests that apple trees and hazelnuts are competing for the similar light resources. Two species with equal canopy heights reduces the GLI of both plants. To avoid light competition and maximize solar capture, multiple canopy systems should not have species sharing the same or similar canopy levels. Canopies should occupy distinct vertical light niches to optimize growth.

Additionally, the model reveals that when the site reaches maturity, some plants will be deprived of adequate light resources. Treatments 4, 5, and 6 all had a large number of cells at or around 0% GLI, most of which were occupied by currants. Currants are a shade tolerant species, but it is doubtful they can tolerate such extremely low levels of light. Poor conditions may result in currants failing to produce a viable crop when the system is at maturity unless there is a large gap between them and the overstory canopy (as in treatment 4). In early stages of system growth, currants may be much more economically viable due to a less developed tree canopy.

Optimal light capture should not be studied only at maturity, but rather at each year in an agroforestry systems growth. When planted, initial heights and canopy widths of all plants are small. Most nut trees will not reach full maturity and nut production until year 12-15 (Hunt et al. 2009) whereas currants are in full fruit production by their 3rd or 4th growing season (Strik & Bratsch 2008). This will allow them to maximize light capture for a few years until trees with greater heights and larger canopies shade them out (Barney 2013). To maximize crop yields, designs of agroforestry systems should not focus only on full site maturity, but also the early stages of growth. Doing so will allow almost all stages of growth to provide a productive crop.

Future Research

There is lack of sufficient data published and shared to produce more accurate tree crop models. SORTIE-ND is used in this study for its simplicity and low level of parameters necessary. The model assumes all trees have cylindrical canopies. However, in reality the shapes of tree crowns can vary from species to species (Fare & Clatterbuck 2000), thus resulting in calculations errors of GLI under tree canopies.

More robust allometric data are necessary to parameterize growth models that run similar light simulations. The SORTIE model in this study is parameterized to run GLI dynamics over the course of a single year. Data over a series of years may prove to be more useful for economic and management decisions. The majority of initial production of the system will be from species that reach maturity first, such as currants, rather than nut trees. Yearly allometric data on woody crop species are needed to understand this further. These data are not readily available in the current literature and should be a focal point to improve modeling of DAS.

Studies are needed to examine the effect of various levels of light on growth and particularly fruit/nut yield of perennial species such as those used in this study. High-density plantings capture more sunlight, but the drop in GLI for understory species may result in significant loss of production. The true effect is unknown because there exist little to no data on optimal light levels of temperate agroforestry species such as those used in this study. There is a need to create light saturation curves for these species. Knowing the proper light levels for optimal growth of biomass or fruits/nuts is essential in designing agroforestry systems.

Lastly, modeling GLI of agroforestry systems may not be sufficient to determine growth and production. Below ground interactions should be included as well (Jose 2004). This model ignores below ground interactions at all times. This may result in high levels of error if using this model to predict growth or yield. The limiting resource may no longer be sunlight when species spacing becomes too dense. Both above and belowground interactions are necessary for accurate predictions of growth of agroforestry systems (Jose 2004).

CONCLUSIONS

This study demonstrates that DAS can be modeled to provide insight into management and layout. The level of light that penetrates through a tree canopy and reaches the layer beneath depends on the plant spacing, opacity of canopies, and the number of canopies. Here, the model shows that the addition of canopy layers at various heights and decreased spacing between plants results in more light being captured by the system as a whole. The additional light, given a ready supply of nutrients and water, may allow for additional plant growth and yield but will require further modeling to test this. Additional research is necessary to continue to fill in knowledge gaps on the optimal design of DAS to maximize light capture, growth, and ultimately fruit/nut production.

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