Using L-systems To Simulate Chickpea Cultivars And Their Shading Abilities

[1]Cici, S.Z.H, [2]B.M. Sindel, [1]S. Adkins and [3]J. Hanan

[1]School of Land and Food Sciences, University of Queensland, [2]University of New England, [3]ARC Centre of Excellence for Integrative Legume Research, ARC Centre for Complex Systems, and Advanced Computational Modelling Centre, University of Queensland. E-Mail: jim@maths.uq.edu.au

Keywords*:* *L-systems modelling; 3D model; plant architecture model; Integrated Weed Management*

EXTENDED ABSTRACT

Plant architecture and light models are invaluable tools for investigating the distribution of light under plant canopies with different architectures. Weed researchers and crop breeders can use such models to investigate the interaction of different canopy architectures of crops with light radiation and its effect on weed phenology.

The crop chosen for this study is chickpea (*Cicer arietinum* L.) as the fourth most important legume in Australian agriculture (FAOSTAT 2004). One of the major obstacles in growing this crop is its poor competitive ability with weeds, which leads to significant reductions in yield. The best method to control weeds in crops such as chickpea is through the use of integrated weed management (IWM). Appropriate IWM packages for chickpea should make use of the competitive ability of specific chickpea cultivars appropriate row spacings, seed densities and timing of crop planting. Having more competitive cultivars appears to be a viable approach for providing a safe and environmentally benign component for IWM.

In the present project, research experiments and modelling approaches were used to determine the important feature(s) of the chickpea canopy architecture to improve its shading ability. Experiments were conducted under controlled conditions with chickpea plants grown on sandy soil with optimum nutrients and water. In order to simulate three-dimensional (3D) architecture of chickpea over time, a 3D digitizer system was used to record the plant morphology (number of organs, leaf area), topology (branching pattern), and geometry (spatial co-ordinates of the plant components) non-destructively.

Modelling is employed to help us to understand and predict how much canopy architecture manipulation may affect light environment and consequently the crop's competitiveness with weeds. In this study, models are expressed using the Lindenmayer-systems (L-systems) formalism which is ideal for coupling plant architecture models to those of environment. A ray tracing program is used to estimate the shading ability of different architectures of chickpea. The results of light simulation were validated with data derived from experiments.

For validating the results of the light model some chickpea plants with different architectures were grown and the amount of intercepted light by plant canopy was measured. Simulations of light interception in different canopy architectures were in good agreement with those obtained from the experiments. The model predictions accounted for 88% of the chickpeas shading abilities observed in the real experiments. Both model and experiments demonstrated that features such as leaflet size and number of branches are more important in improving shading ability than the branching angle.

It is concluded that models like L-systems can be valuable for studying the shading ability of different cultivars, but there are some limitations. It is hoped that this 3D model can provide the basis for modeling the interference of different canopy architectures of chickpea with a target weed. However, due to the morphological plasticity of weeds in competition with crops more work will be required to model the response of a particular weed to the shading ability of chickpea.

1. INTRODUCTION

Weed management is one of the most significant problems faced in crop production. Weeds compete with crops for light, water and nutrients. The canopy architecture of plants is a factor that has important effects on light environment and consequently neighbouring plants. Differences in canopy forms may affect photosynthetically active radiation, and light signaling on neighbouring plants (Aphalo *et al.* 1999).

One of the best approaches in controlling weeds is using an integrated weed management (IWM) package. The development of competitive ability of crops is one of the safest and most environmentally benign components in IWM. Generally speaking, procedures for selecting genotypes with an improved above ground competitive ability can be categorized into two main classes: direct selection (in the presence of weeds) and indirect selection (in the absence of weeds by comparing shading ability) (Lemerle *et al.* 1996). It has been well documented that features such as rapid germination, early above ground growth, large leaf area development, and increased plant height and number of branches can improve the shading ability of a crop leading to the suppression of weeds (Christensen 1995). It has been stated by Challaiah *et al.*(1986) that shading ability is the best trait to account for above-ground varietal differences in wheat. However the response of target weed to available light should not be ignored.

As one of the most important grain legumes in Australian agriculture (FAOSTAT 2004), Chickpea (*Cicer arietinum* L.) has been chosen in this study. One of the major obstacles in growing this crop is its poor above-ground competitive ability with weeds, which leads to significant reduction in yield. Unfortunately, differential shading and competitive abilities among existing chickpea varieties have not been documented. Before embarking on breeding, doing laborious and time consuming breeding experiments one should establish how much the chickpea architectures are different in their shading ability and how important this shading ability may be in improving the competitive ability of chickpea with target weeds.

Using mechanistic competition models is one way to identify key traits with respect to competitive ability. To date, two simulation models have been proposed for ranking rice (Bastiaans *et al.* 1997) and wheat (Olesen *et al.* 2004) competitiveness against weeds. These modelling approaches rely on growth rate, leaf area and height of plants, but does not account for the actual position of leaves within the canopies.

Alternatively, functional-structural plant models (FSPMs) take the structure of plant components into account while modeling the development (Godin and Sinoquet 2005). The models are based on simulating the growth and development of plants in a three-dimensional (3D) space. The L-systems formalism is one of the programming tools that can be used to generate 3D virtual plants. After defining a set of developmental rules, the simulation program can compute plant growth and development step by step and produce 3D models of the plant (Prusinkiewicz 1998). These architectural models of plants can be coupled with environmental models to investigate the plant interaction with its environment including neighbouring plants (Mech 1997). Many 3D models of light interception and transfer by plants have been developed using the L-systems formalism (Allen *et al.* 2005; Gautier *et al.* 2000). The models of light can be volume based, surface based, or a combination of these two methods (Chelle and Andrieu 1999).

The present work aims to simulate the shading ability of different chickpea architectures and investigate the potential of L-systems as a tool for ranking and designing varieties for this feature. To date, there has been no model on chickpea architecture and its shading ability. First a thermal time model of chickpea architecture relying on empirical observations is developed. Then, light interception of different chickpea architectures is simulated and its viability as a research tool is discussed.

2. METHODS

2.1. Data Acquisitions and Analysis

Experiment I- Data for constructing the chickpea plant model: An experiment was conducted under controlled conditions in 2005 at the University of Queensland in St_Lucia, Queensland. Thirty chickpea plants (Desi type, variety 960331014) were grown in sandy soil in a glasshouse at an average air temperature of 21 ± 2ºC. Optimum water and nutrients were provided and crop density was 40 plants m^{-2} with 20 cm row spacing. The growth and development of plants were monitored every two days and digitized every week. Topology and geometry of chickpea plants were captured by a sonic digitizer (Model GP12-XL). A sonic digitizer has a triangle with three microphones, a probe with two sound emitters, and a processor (Hanan and Room 1997). The equipment takes advantage of the fact that sound travels between two points at a constant speed. By pulling a trigger on the probe, the processor fires sound emitters. The processor calculated the position of 3D coordinates based on the time taken for the sounds to reach each microphone. The Floradig software (Hanan and Room 2002) records 3D coordinates, which were then converted into geometric properties such as the internode length, and the angle between the main stem and branches. Linear and non linear regressions (MINITAB 14) were fitted to the data to parameterize geometrical attributes for the plant model.

Experiment II- Data for validating the light model: Six different canopy architectures were generated from 3 different varieties 960331014, ICC3996, and 91ETA6021. Three more architectures were generated by manipulating variety 960331014. Branches, for example, were spread out to increase branching angles or tied up to reduce branching angle or some of the branches were removed to create sparsely branched architecture. Crop density and row spacing between plants was 40 plants m^{-2} and 20 cm, respectively. The canopy features of these chickpeas were recorded every 10 days. Twenty and forty days after the appearance of the first node, photosynthetic photon flux density (PPFD) at ground level and incident PPFD above the chickpea plants were measured with a line quantum sensor (LI-1000, LI-Cor, Lincoln, NE) between 12:00 and 14:00 h. Three crossed-pair readings were taken at ground level and averaged. Percent canopy PPFD interception was obtained by subtracting the ground level readings, expressed as percent of the incident radiation above the canopy, from 100.

2.2. Plant Model Description and Parameterization

The hypothetical basis behind this model is L-systems (Lindenmayer 1968, Prusinkiewicz 1990). L-systems are string rewriting techniques that can be used to model the morphology of a variety of organisms. An L-system consists of an initial axiom, an alphabet (a set of modules i.e. symbols with associated parameters) and a set of production rules. The rules take the form

$$Predecessor \rightarrow successor$$

where a string of modules matching the *predecessor* produces a string of modules derived from the *successor* string in the next step. For example, the rule :

$$A \rightarrow I[L]A$$

causes the predecessor (A) to produce a successor that consists of an internode 'I', a leaf 'L', and an ongoing apex 'A'. Modules represent each of the components of plant, such as 'I' for internode, with parameters characterizing properties of the components such as geometrical properties, or physiological attributes. For example, to double the length of leaf in every step, a production can be written as

$$L(x) \rightarrow L(2 \times x)$$

Topological aspects of a plant in L-systems are driven by putting components in square brackets '[ ]' to define branches and by the order of modules.

The chickpea model presented in this paper starts with a single apical meristem (apex) with associated node and degree-day parameters. The rate of growth and development of this model is correlated with thermal time allowing the model to run in steps of days based on growing degree-days (GDD). Using GDD provides a means of relating plant growth to air temperature (Clapham and Fedders 2004).

Development is expressed in terms of the phyllochron, which is the time interval or number of degree-days needed between the appearances of successive nodes (Hanan 1997). Phyllochron was calculated by dividing the sum of GDD needed from germination till 50% seed setting into the number of nodes. GDD is calculated by the equation (1):

$$GDD = [(T_{max}+T_{min})/2 - T_{base}] \quad (1)$$

T_{max} and T_{min} are maximum and minimum temperatures in each day during growth and development of plant, respectively. T_{base} is the minimum temperature that a plant needs to germinate and is 0ºC for chickpea.

The data used to parameterize the model are summarized in Table 1.

Table 1. Summary of parameters and values used in the plant model - cultivar 960331014

Parameter	Value
Max internode length (MAXI)	2 cm-3 cm
Max leaflet length (MAXL)	1.2 cm
Main stem bending (MSB)	5 º
Branching angle (MBA)	20 º
Delay of branching (DEL)	7

2.3. Light Model Description and Parameterization

The plant model can be interfaced for bilateral communication with an environment model (Mech 1997). The environment model is an active process that reacts to the information from the plant model. The position and orientation of leaves of virtual chickpea are passed to the light model and act as an obstacle for light resulting in light distribution in the canopy being determined by plant geometrical pattern. The chickpea model is coupled with a light model to calculate the distribution of light in the canopy using a Quasi-Monte Carlo method (a sub category of Monte-Carlo ray tracing method) (Cieslak 2003). Light sensors can be placed in any desired pattern under the canopy. In this case, 50 × 100 array of sensors covering the ground beneath the canopy was simulated.

The light model is set to run 1000 times with different random seeds in order to estimate the variance in the light readings. The direction of light source in this virtual experiment was set to 0.5, -0.86, and 0.0 which are x, y, and z directions for July at noon time in Brisbane, Queensland. The value of wavelength λ (660 nm) is specified in the model as well. The data used to parameterize the plant model for different architectures of chickpea were estimated from experiment II and are summarized in Table 2.

Percent canopy PPFD interception was obtained by subtracting the sensor readings, expressed as percent of the incident radiation above the canopy, from 100. Both histograms and the Kolmogorov-Smirnov test for two independent samples (KS test) were used to interpret the results of the light simulation. The Spearman's rank correlation coefficient (MINITAB 14) was used to measure the degree of linear relationship between simulated and observed results.

Table 2. Input parameters to determine the worst and best canopy architectures with the view to determine the shading ability

Canopy	Abb.	MAXL	MSB	MBA	Branch Count
Desi type -cultivar 960331014					
Densely branched	DB	1.2 (cm)	5	20	4
Sparsely branched	SB	1.2	5	20	2
Large branching angle	LBA	1.2	10	35	4
Small branching angle	SBA	1.2	1	3	4
Desi type - Cultivar ICC3996					
Small leaflet	SL	0.8	5	10	4
Kabuli type - Cultivar 91ETA6021					
Large leaflet	LL	1.5	5	15	4

3. RESULTS

3.1. Simulation of Chickpea

The development and topology of chickpea is visually presented (Figure 1). The processes of flowering and leaf senescence were not parameterized in this model. The most important aims of constructing this model were:

- to simulate different architectures of chickpea by changing some geometrical features such as leaflet size and branching angles based on available cultivars
- to couple the plant model with a light environment model to simulate light under different chickpea canopy stands

Figure 1. Side view of virtual chickpea plants, at 160 and 350 GDD from left to right in the top row, and 1035 GDD in the bottom row

3.2. Simulation of Light Interception by Different Canopy Architectures of Chickpea

Different canopy architectures of chickpea were simulated on the basis of the observed data from different chickpea cultivars. The model simulated a density of 40 plants m^{-2} with 20 cm row spacing as used in the real experiments. The Quasi-MC light model was used to predict the effect of different architecture scenarios on light environment (Figure 2).

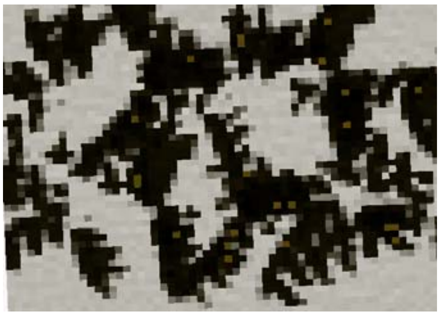

Figure 2. Visualization of the simulation of light under the canopy of chickpea plants from above: the gray and black squares are sensors under the chickpea stands; the darker ones indicate the lower amount of light reaching them

For simplicity, each variety pair was compared with regard to a particular architectural feature. For example, the shading ability of simulated plants with small leaflets was compared to those with large leaflets. Graphs in Figure 3 show the comparison of the effects of different chickpea architectures on the pattern of intercepted light by the plant canopy. In the histograms (Figure 3), if the distribution is more skewed to the right than left then the shading ability of the simulated architecture will be higher.

In plants with large leaflet architecture (Figure 3 A), the amount of light intercepted was higher than the amount in plants with small leaflets (Figure 3 B). The symmetrical distribution in the middle of the x axis and a skewed distribution to the left in Figure 3 B indicate how poor its shading ability, and consequently its aboveground competitive ability, is. The frequency ($f_{(x)}$) distribution of light interception was not markedly different between the architecture of small branching angle (Figure 3 C) and large branching angle (Figure 3 D). The distribution has an obvious tail to the left in the sparsely branched architecture (Figure 3 F) in comparison with the densely branched one (Figure 3 E).

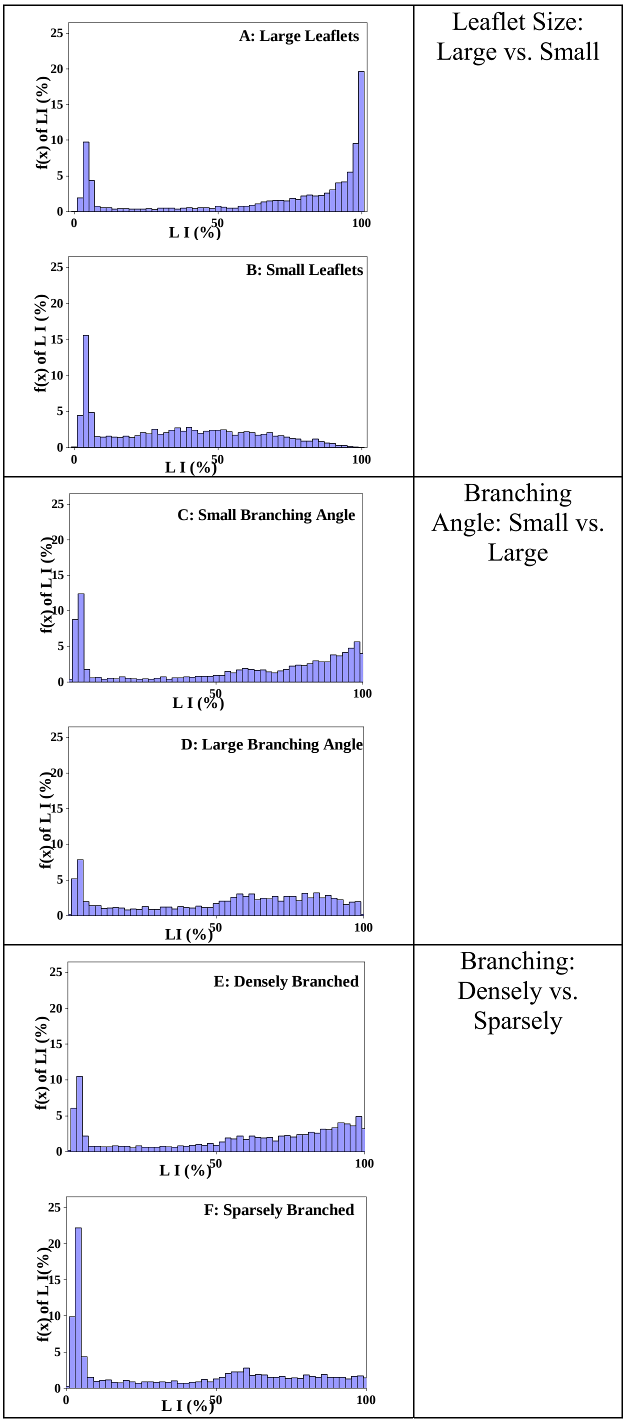

Figure 3. Comparison of the effects of architectures of chickpea on frequency ($f_{(x)}$) distribution (density) of light interception (LI) by the plant canopy

While these histograms show the distribution of light interception, the KS test was used to test whether two independent simulations were statistically the same or not. This test is sensitive to any kind of distributional differences. Since the KS test was > the critical value (c.v.) it is concluded that there was a strong likelihood that architectures in each compared pair were different in their shading abilities (Table 3).

Table 3. KS test to compare the statistical difference between two patterns.

Different architectures[*]	**KS test**	**c.v.**
SL and LL	47	0.019
SBA and LBA	15	0.019
DB and SB	20	0.019

[*] Abbreviations as in Table 2

3.3. Model Validation

The Spearman rank-order correlation indicated a strong positive association of ranked simulation and observed intercepted light (experiment II) by chickpea canopy ($r=0.91$, $p<0.05$).

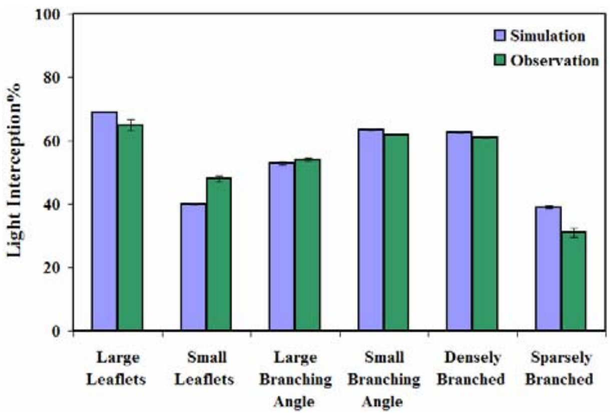

Figure 4. Comparison of simulations and observed data of the effects of chickpea architectures on the amount of light intercepted%

For the same growth degree days, light interception was related to plant architecture in both simulation and field experiments. Light interception was higher in plants with larger leaflets, smaller branching angle and dense branching in both model simulation and field observations (Figure 4).

4. CONCLUSIONS

Good agreement was obtained between the estimated light interception through the simulated canopies of chickpea and measurements. By using 3D models of chickpea architectures interfaced with the light model, the distribution of intercepted light could be estimated for various chickpea architectures. The main advantage of this model is its application to various management designs, such as row spacing or plant density. It is also possible to simulate each architectural parameter (geometry) easily in L-systems.

The model could be used to assess the effect of chickpea architecture on a target weed. Once the architectural features of both crop and target weed have been determined, a great amount of field work can be saved by testing many different weed management options with virtual experiments. The method described here has two main limitations. The first one is the computation time required and the second is the large number of field measurements needed to develop a 3D model of plant growth and development.

Although this is a work in progress, its usefulness for research and education seems promising. In its current state, the model is able to predict the shading ability of different architectures of chickpea stands accurately. The next phase of this project is to simulate the effect of canopy of chickpea on the growth and development of sowthistle (*Sonchus oleraceus* L.), one of the emerging weeds. It is hoped that this project will lead to the design of more competitive chickpea varieties to suppress target weeds. A better understanding of the process of the effects of crop architecture on light environment may contribute to future improvements in the simulation of crop interference with weeds.

5. ACKNOWLEDGMENTS

This work is supported by operation funds from the CRC for Australian Weed Management. Thanks are extended to Mr Ted Knights, chickpea breeder in NSW, for his help and provision of chickpea seeds. We also thank Mr Tim Rudge for assistance with the light program.

6. REFERENCES

Allen MT, Prusinkiewicz P and DeJong TM (2005), Using L-systems for modeling source-sink interactions, architecture and physiology of growing trees: the L-PEACH model. *New Phytologist*. 166: 869-880.

Aphalo PJ, Ballare CL and Scopel AL (1999), Plant-plant signalling, the shade-avoidance response and competition. *Journal of Experimental Botany*. 50: 1629-1634.

Bastiaans L, Kropff MJ, Kempuchetty N, Rajan A and Migo TR (1997), Can simulation models help design rice cultivars that are more competitive against weeds? *Field Crops Research*. 51: 101-111.

Challaiah, Burnside OC, Wicks GA and Johnson VA (1986), Competition between winter wheat (*Triticum aestivum* L.) cultivars and downy brome (*Bromus tectorum* L.). *Weed Science*. 34: 689-693.

Chelle M and Andrieu B (1999), Radiative models for architectural modelling. *Agronomie*. 19: 225-240.

Christensen S (1995), Weed suppression ability of spring barley varieties. *Weed Research*. 35: 241-247.

Cieslak M (2003), *QuasiMC user's manual*. pp. 10. University of Calgary, Calgary.

Clapham WM and Fedders JM (2004), Modeling vegetative development of clover (*Trifolium alexandrinum* L.) as a function of growing degree days using linear regression and neural networks. *Canadian Journal of Plant Science*. 84: 511-517.

FAOSTAT (2004), FAOSTAT data. http://apps.fao.org/faostat/notes/citation.htm/ Last Accessed May 4, 2005.

Gautier H, Mech R, Prusinkiewicz P and Varlet-Grancher C (2000), 3D architectural modelling of aerial photomorphogenesis in white clover (*Trifolium repens* L.) using L-systems. *Annals of Botany*. 85: 359-370.

Godin C and Sinoquet H (2005), Functional-structural plant modelling. *New Phytologist*. 166: 705-708.

Hanan J (1997), Virtual plants - integrating architectural and physiological models. *Environmental Modelling & Software*. 12: 35-42.

Hanan J and Room P (1997), Practical aspects of virtual plant research. In *Plants to ecosystems*. Ed. Michalewicz MT. pp. 28-44. CSIRO, Melbourne.

Hanan J and Room P (2002), *Floradig, user manual*. pp. 52. CPAI, Brisbane.

Lemerle D, Verbeek RD, Cousens RD and Coombes NE (1996), The potential for selecting wheat varieties strongly competitive against weeds. *Weed Research*. 36: 505-513.

Lindenmayer A (1968), Mathematical models for cellular interaction in development, Parts I and II. *Journal of Theoretical Biology*. 18: 280-315.

Mech R (1997), Modelling and simulation of the interaction of plants with the environment using L-Systems and their extensions. PhD thesis, University of Calgary, Calgary.

Olesen JE, Hansen PK, Berntsen J and Christensen S (2004), Simulation of above-ground suppression of competing species and competition tolerance in winter wheat varieties. *Field Crops Research*. 89: 263-280.

Prusinkiewicz P (1990), Exploring the beauty of plants. *Computer Graphics and Applications*. 10: 3-6.

Prusinkiewicz P (1998), Modeling of spatial structure and development of plants: a review. *Scientia Horticulturae*. 74: 113-149.

Prusinkiewicz P, Karwowski R, Mech R and Hanan J (2000), L-studio/Cpfg: A software system for modeling plants. *Lecture Notes in Computer Science*. 1779: 457-464.