ISSN: 394 7990
Malaysian Journal of Soil Science Vol. 7: 17-27 (2003) Malaysian Society of Soil Science

3-D Direct Solar Radiation Regime of Maize (*Zea mays* L.)

C.B.S. Teh

Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ABSTRACT

The main objective of this study was to develop and test a 3-D solar radiation model for maize (*Zea mays* L.). The model was developed by dividing the canopy space of maize into a network of 3-D cuboids, and for each cuboid, three properties were determined: 1) leaf area, 2) leaf orientation, and 3) mean travelling distance of a solar beam. These three properties were determined using the polygon clipping and ray-tracing algorithm. Then Beer's law was used to determine the solar irradiance for the given cuboid. A maize field experiment (18x18 m, planting density of 6 plants m^{-2}) was also conducted to test the model's accuracy. The canopy architecture of 3–6 maize plants was measured weekly starting 27 days from sowing. Solar irradiance was also measured diurnally. The model was shown to be accurate (mean error of 6%) when applied to all growing stages of maize, with no overall tendency to either over or underestimate the fraction of captured solar radiation. The simulated 3-D plant-radiation regime showed that the diurnal changes in the spatial plant-radiation profile for sparse canopies (leaf area index of 0.9) was more varied than that for almost closed canopies (leaf area index of 2) which was more uniform and less diverse.

Keywords: Solar radiation, maize, canopy architecture, light interception, model

INTRODUCTION

Simple 1-D solar radiation models are usually used to model the solar irradiance regime within the plant canopies. Though easy to use and requiring few and simple inputs, these 1-D models are often inaccurate when applied to field conditions of sparse canopies, young plants, row planting, mixed canopies, or in attempts to model the plant-radiation regime of a single crop rather than the usual entire cropping system. This is because 1-D models are often based on Beer's law, which assumes homogeneity of canopy cover, achieved in conditions of a closed, random mixing of canopies. Consequently, the use of a more complex 3-D solar radiation model is required in conditions when the simulations from a simpler 1-D model are not sufficiently accurate. Additionally, a 3-D model would provide an in-depth description of how much solar radiation was captured by the entire canopy and more interestingly how the solar irradiance varied spatially within the canopies, and how much solar radiation was captured by the various parts of the canopy. This provides opportunities to study the effects of various conditions on a plant's ability to capture solar radiation, such as in conditions of different planting densities or row planting direction (or patterns), leaf pruning, environmental stress, and in mixed cropping.

The main objectives of this study were: 1) to develop and test a 3-D solar radiation model for maize; and 2) to determine the changes in the plant-radiation regime in the maize environment at various hours of a day as well as at various stages of crop growth.

MATERIALS AND METHODS

Model Development

The canopy space of maize was divided into a network of 3-D cuboids that was perpendicular to the planting row direction *(Fig. 1)*, where for each cuboid, three types of information were required: (a) leaf area density (leaf area per unit volume of canopy); (b) leaf orientation distribution (G-function); and (c) the mean travelling distance of a solar beam within the cuboid. In this study, the canopy aerial space was divided into 20 by 20 by 20 number of cuboids. The probability (P_k) of a single solar beam reaching the *k*-th cell in the network was calculated by:

$$P_k = \prod_{c=1}^{k} \exp\left(-G_c(r) \cdot \rho_{f,c} \cdot s_c \cdot \sqrt{1-\sigma}\right) \tag{1}$$

where the multiplicative series c=1 to (k-1) represents every cell traversed successively by a solar beam in reaching the target cell k; P_{fc} is the leaf area density in the c-th cell; *Sc* is the beam path length in the c-th cell; σ is the leaf scatter coefficient, taken as 0.20 for maize (Tournebize and Sinoquet 1995); and *Gc(r)* is the G-function in the c-th cell (Sinoquet and Bonhomme 1992). The *G*-function *G(r)* is regarded as the average projection per unit foliage area in the sun direction *r*, where the sun direction is described by inclination θ and azimuth ϕ. The *Gc(r)* in the c-th cell was calculated by:

$$G_c(r) = G_c(\theta,\phi) = \frac{\sum_{j=1}^{N} L_{c,j} \left| \cos\theta \cos\theta_L + \sin\theta \sin\theta_L \cos(\phi - \phi_L) \right|_{c,j}}{\sum_{j=1}^{N} L_{c,j}} \tag{2}$$

where $L_{c,j}$ is area of the j-th leaf in the c-th cell; N is total number of leaves in c-th cell; and θ_L and ϕ_L are the leaf normal inclination and leaf normal azimuth of the j-th leaf in the c-th cell, respectively (Thanisawanyangkura *et al.* 1997). Calculations for sc were based on simple geometry as described by Gijzen and Goudriaan (1989) and Sinoquet and Bonhomme (1992).

Finally, the 3-D model adapted algorithms from the field of computer graphics, namely the polygon clipping algorithm (Vatti 1992) to determine the portion of a

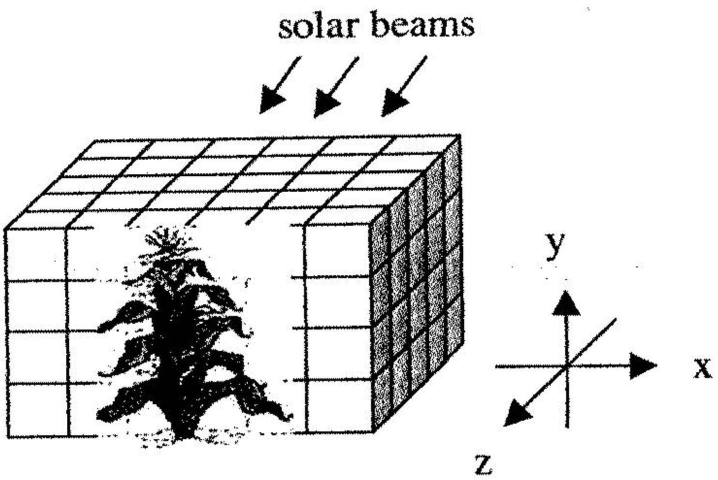

Fig. 1: The canopy aerial space of maize is divided into a network of 3-D cuboids

maize leaf encompassed by a given 3-D cuboid, and ray-tracing algorithm to track the traversal of solar beams into the canopy.

Field Experiment

To test the accuracy of the 3-D solar radiation model, model simulations were compared against actual measurements from a field experiment at various stages of crop growth. Maize (*Zea mays* L.) was planted in a north-south row direction at Field No. 2, UPM (3°01'N, 101°42'E) on 5 June 2002. Field size was 18 by 18 m, with six plants per m^2 ground area. Inter- and intra-row spacings were 0.6 and 0.3 m, respectively. Canopy architecture measurements on maize started 27 days after sowing (DAS) and continued every seven days for seven weeks. For each data collection period, three to six maize plants were randomly selected and all leaves in a plant were measured for leaf azimuth, inclination and area (Lemeur 1973). Solar irradiance above and below canopies was also measured diurnally during the data collection days, using a canopy transmission meter (Model EMS 7, Hitchin, Hertfordshire, UK) levelled horizontally and in perpendicular to the planting row direction.

RESULTS AND DISCUSSION

The 3-D solar radiation model did not show an overall tendency to over- or underestimate the fraction of solar radiation captured by maize (*Fig. 2f*). Moreover, the model mean absolute error (i.e., absolute difference between the simulated and measured values) was 0.06 or 6%. *Figs. 2a-e* also show that the solar radiation interception depended on the solar position, whereby the solar radiation interception decreased gradually as the sun begun to align in parallel to the planting row direction (N-S). Solar radiation interception was the lowest at 14:00 hours, and after this hour, solar radiation interception begun to increase. The effect of a pronounced planting row direction on solar radiation capture has often been observed (Wallace

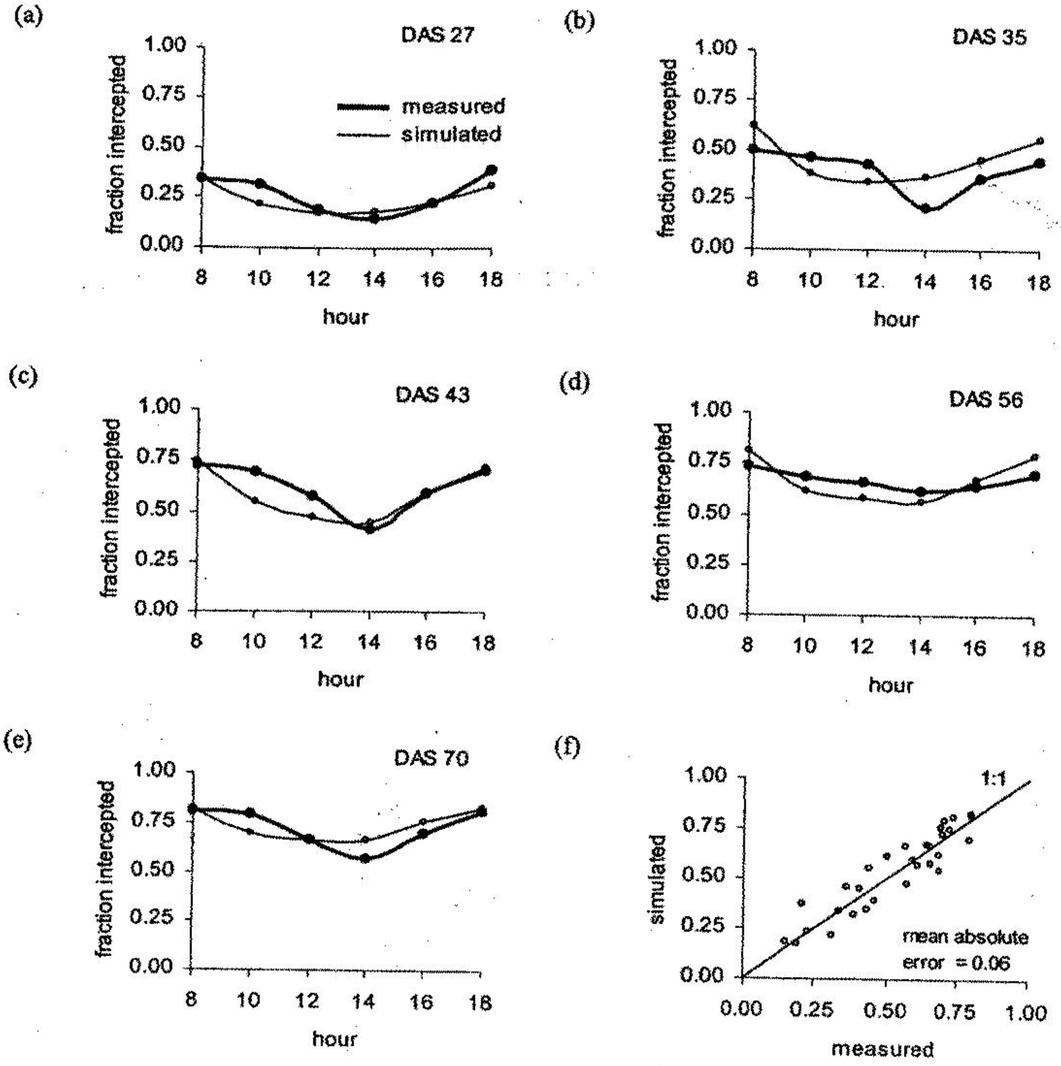

Fig. 2: Comparisons between the measured and simulated fraction of solar radiation captured by maize. Note: the last chart (f) shows the overall comparisons between the measured and simulated values for all data collection days (DAS 27-70).

1997). This effect arises because when the sun is parallel to the planting row direction the "impediment" by the maize canopies on solar beams is less as compared to that when the sun is non-parallel to the planting row direction *(Fig. 3)*. More importantly, however, the observed diurnal trend of solar radiation interception was simulated closely by the 3-D model, except for DAS 35 *(Fig. 2b)*. Errors in the model simulations could be reduced by modelling the diffuse solar radiation as well. Currently, the 3-D model only accounted for direct solar radiation.

Fig. 4 shows five sequential cross-section maps of the maize aerial space depicting the solar penetration probability from the canopy top to the soil surface on DAS 27. In these maps, the dark areas depict low solar irradiance due to the difficulty or low probability of solar beams reaching these areas. In contrast, bright areas in the maps depict high solar irradiance due to their high solar penetration

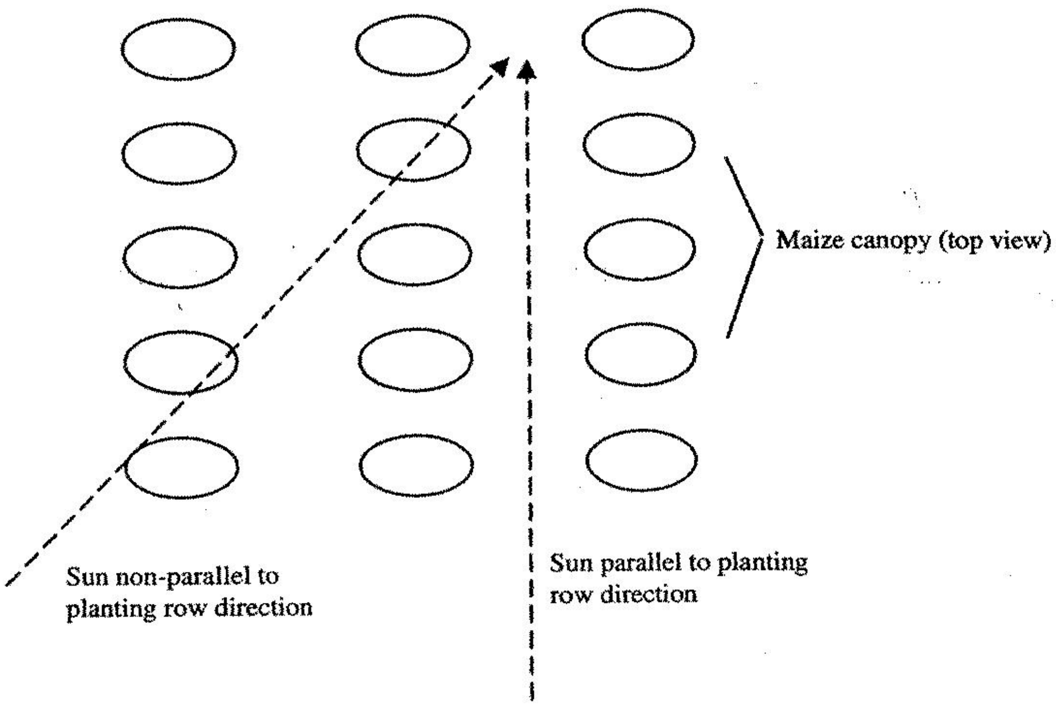

Fig. 3: Canopy impediment to solar beams for two solar directions

probability. Overall, the solar irradiance was the highest and lowest at the canopy top and bottom (or ground level), respectively. This was because increasingly more solar radiation would be intercepted by increasingly more maize leaves as the solar beams traversed deeper into the canopy. The proportion of dark regions was greater than the proportion of bright regions within the maize canopy for low solar elevations such as in the early mornings or late evenings (e.g. compare *Fig. 4a* and *4f* with *Fig. 4c* and *4d*). This was because at low solar elevations, the solar beams faced greater impediment by the maize canopy to reach, for example, the soil surface. There was also a gradual shift of the dark regions from the West (i.e., left side of maps) to the East (i.e. right side of maps), and vice versa for the bright areas, which would shift from east to west. This was due to the sun movement as it rose from the east and moved towards the west as the day progressed. As the sun aligned in parallel to the planting row direction, the dark areas within the maize canopy decreased as increasingly more solar beams reached the soil surface, unintercepted by the maize plant. At 14:00 hours when the sun was parallel to the planting row direction, the dark areas were limited to the regions around the plant stem *(Fig. 4d)*. As shown by *Fig. 3, Fig. 4d* is almost akin to a silhouette of the maize plant when the sun was parallel and shone along the planting rows.

The above trend continued even as the maize plant matured *(Fig. 5)*. However, the proportion of dark areas within the maize canopy on DAS 43 was larger than that on DAS 27 because of the increased ground cover and leaf area index (from 0.9 to 2.0 m2 m-2); thus, intercepting more solar radiation on DAS 43 as compared to DAS 27. At low solar elevations *(Fig. 5a* and *5f)*, only a "thin slice" of the

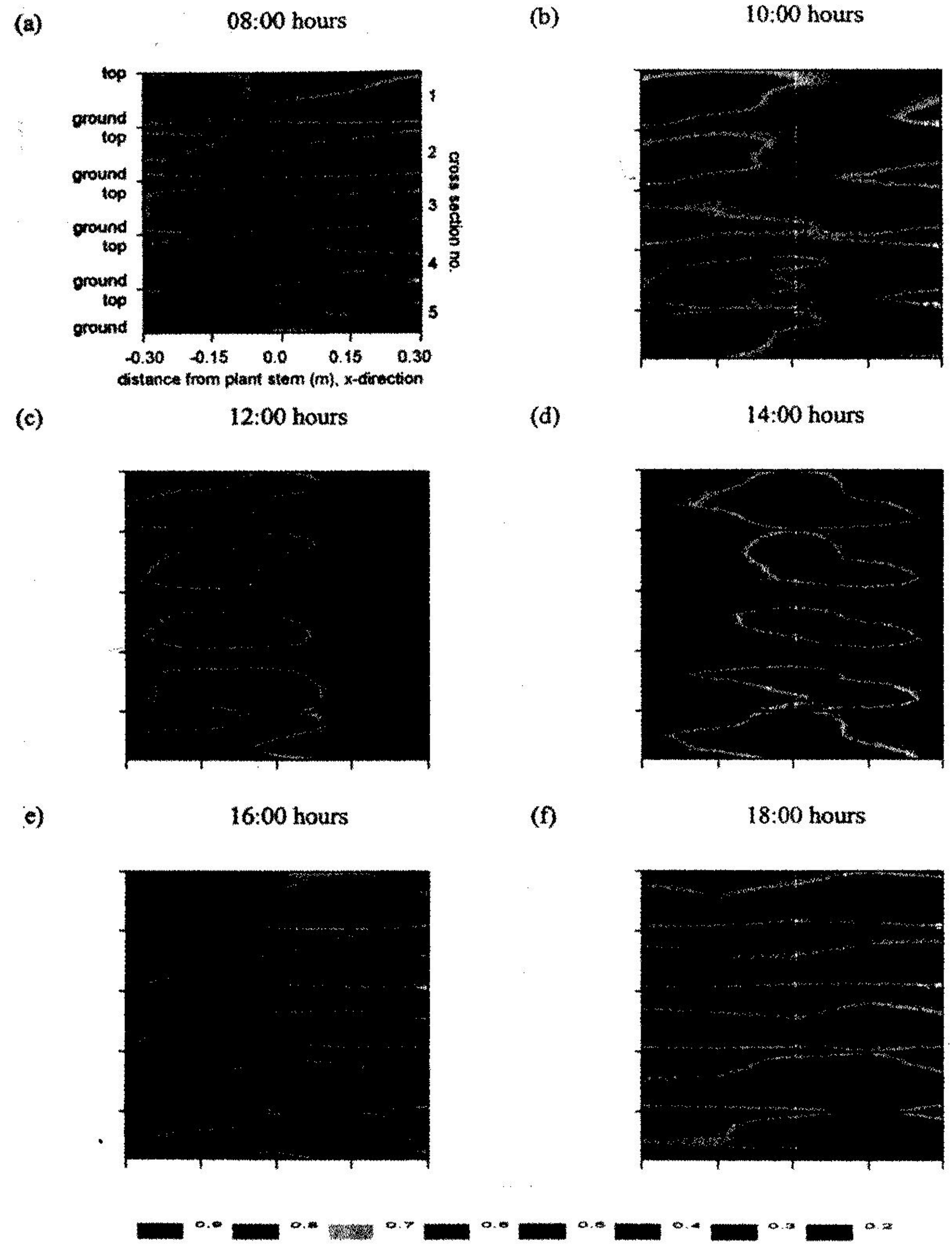

Fig. 4: Five cross-section maps of the maize aerial space depicting the solar penetration probability from the canopy top to the ground (soil) surface on DAS 27. All cross-sections are perpendicular to the north-south planting row direction.

Note: the north and south directions are facing into and out of the paper, respectively.

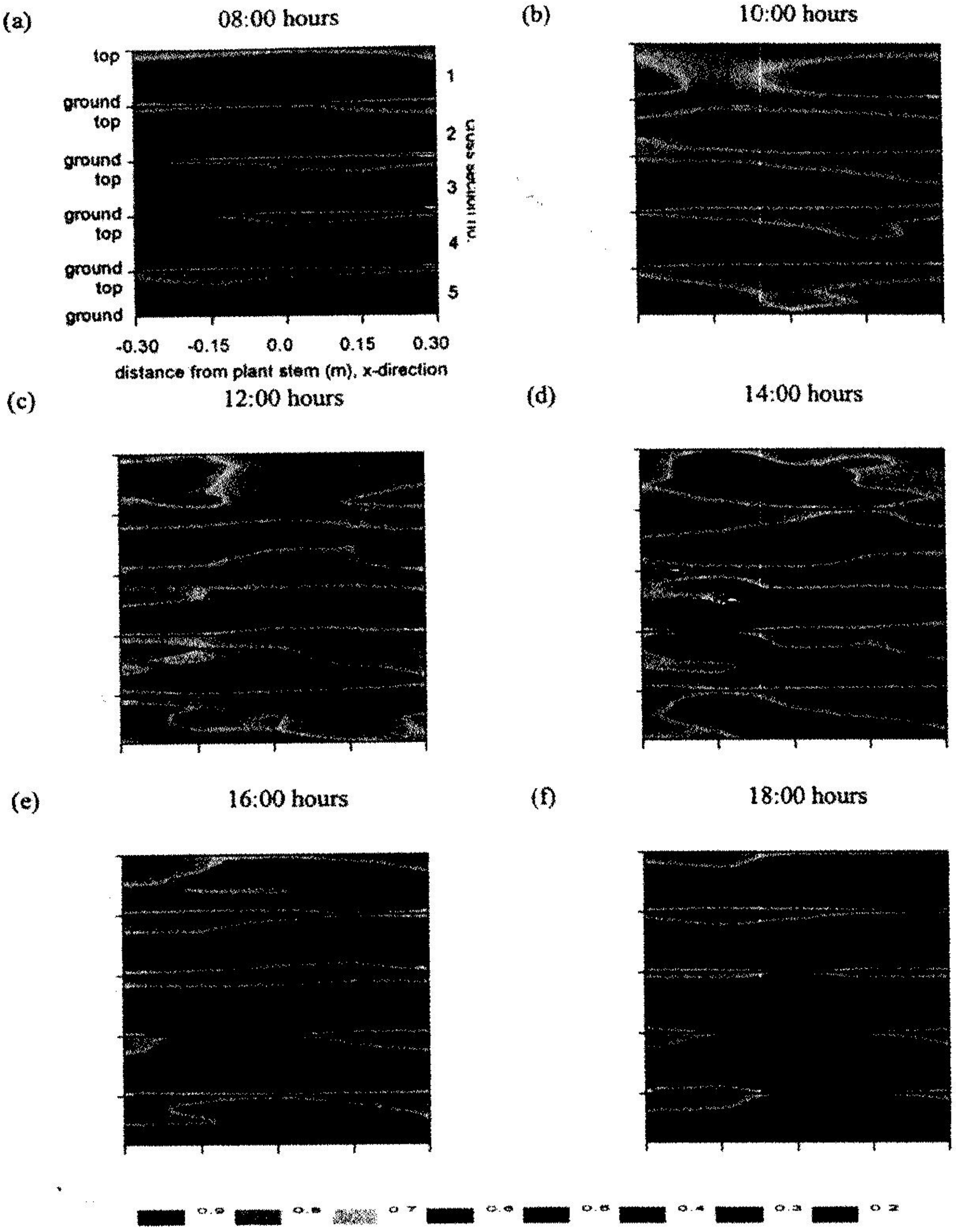

Fig. 5: Five cross-section maps of the maize aerial space depicting the solar penetration probability from the canopy top to the ground (soil) surface on DAS 43. All cross-sections are perpendicular to the north-south planting row direction.

Note: the north and south directions are facing into and out of the paper, respectively.

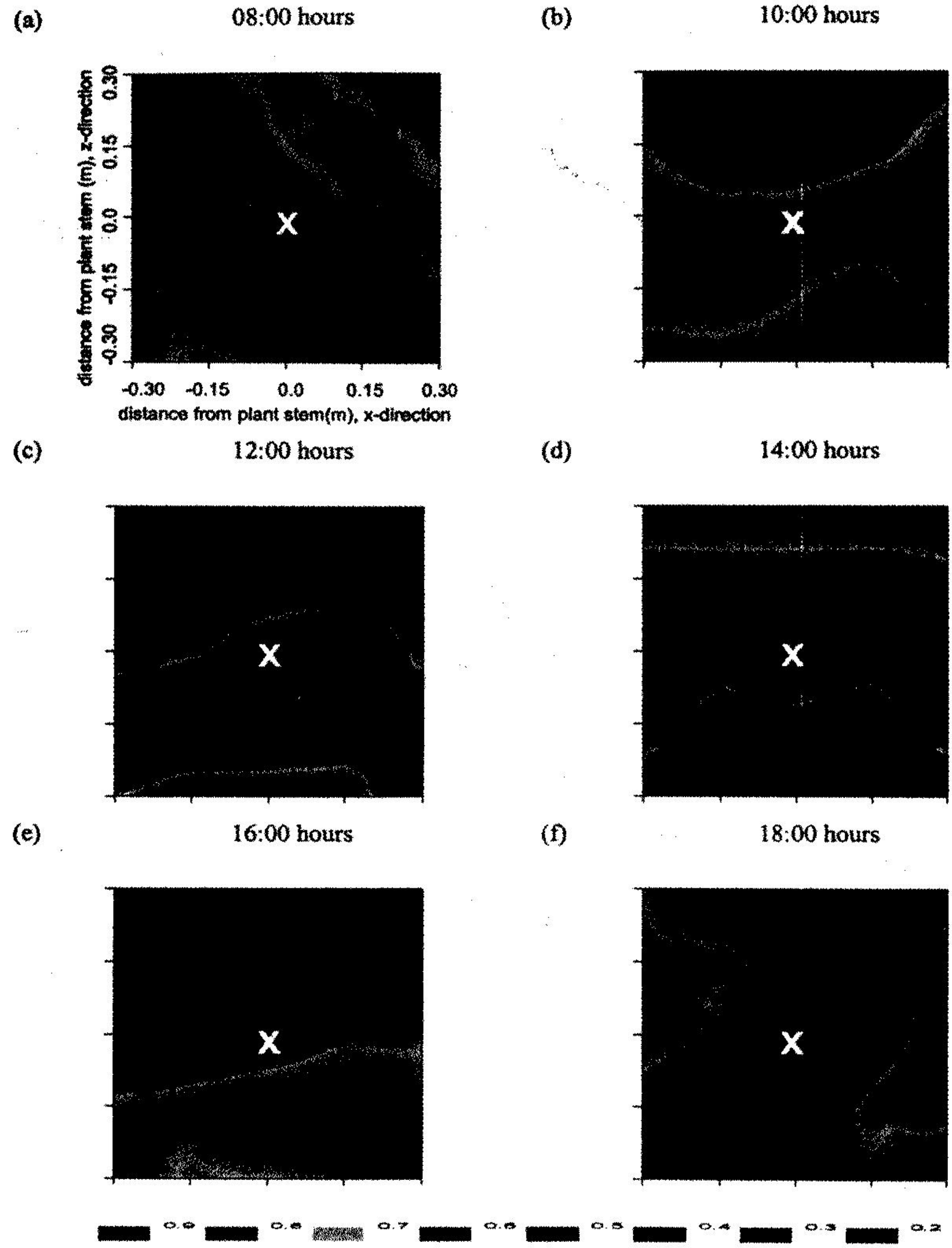

Fig. 6: Spatial map of the ground (soil) surface showing the solar penetration probability on DAS 27. Note: 'x' indicates the maize stem location, and 'N' the north direction.

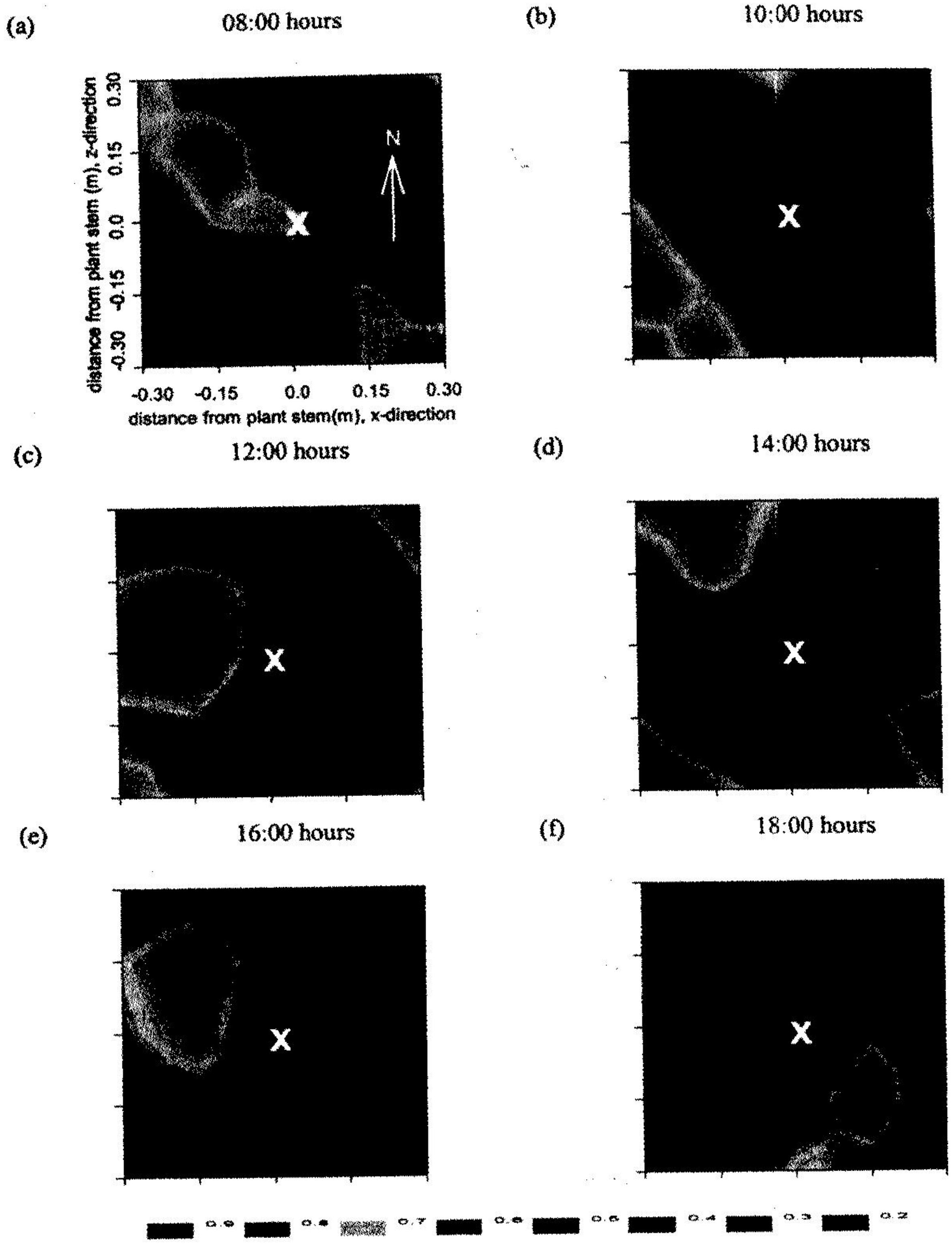

Fig. 7: Spatial map of the ground (soil) surface showing the solar penetration probability on DAS 43. Note: 'x' indicates the maize stem location, and 'N' the north direction.

canopy top was illuminated as the solar beams faced an even greater impediment by the larger leaf area of maize on DAS 43 compared to the canopy impediment on DAS 27. Both *Figs. 4* and *5* show why the simpler 1-D solar radiation model is often inaccurate because it assumes canopy homogeneity, whereas both *Figs. 4* and *5* clearly showed a great deal of canopy heterogeneity, especially for the early crop growth period *(Fig. 4)*.

Fig. 6 shows the spread of both the dark and bright areas on the soil surface on DAS 27. In the early morning (08:00 hours), there appeared alternating bands of dark and bright areas *(Fig. 6a)*. And these bands would rotate counter clockwise, following the sun movement as the sun shifted from east to west during the day *(Fig. 6b-f)*. This trend, however, was less noticeable on DAS 43 *(Fig. 7)* due to the increased ground cover and leaf area index of maize. This was also why there was a greater proportion of dark areas on the soil surface on DAS 43 compared to that on DAS 27.

CONCLUSIONS

Despite accounting only for the direct component of solar radiation, the 3-D solar radiation model showed overall good accuracy in simulating both the total solar radiation captured by maize and the diurnal trend of solar radiation interception for all stages of crop growth. The 3-D model was also useful to describe the spatial changes in the solar irradiance regime within the maize canopies which showed that the spatial solar irradiance regime within the maize environment was more diverse or varied for sparse canopies (DAS 27) compared to almost full canopy (DAS 43).

This work is on-going with the immediate plan being to account for the diffuse component of solar radiation. This can be done by dividing the whole sky into several regions (40 regions, described by 5 and 8 inclination and azimuth angles, respectively), and "pushing" several solar beams into the 3-D network of maize canopy from each of these sky regions, thus simulating diffuse solar radiation beams. The immediate plan will also include adapting the current 3-D solar radiation model for oil palm. However, this task is challenging as oil palm is larger in size and has much more leaves (fronds and leaflets) than maize. Thus, model computations are expected to be more intensive and time-consuming.

ACKNOWLEDGEMENTS

The author is grateful for the financial support extended under the UPM New Lecturer Research Scheme (No. 53102). The assistance provided by En. Zairizal b. Zainon is acknowledged.

REFERENCES

GIJZEN, H. and J. GOUDRIAAN. 1989. A flexible and explanatory model of light distribution and photosynthesis in row crops. *Agric. For. Meteorol.* **48:** 1-20.

LEMEUR, R. 1973. A method for simulating the direct solar radiation regime in sunflower, Jerusalem artichoke, corn and soybean canopies using actual stand structure data. *Agric. Meteorol.* **12**: 229-247.

SINOQUET, H. and R. BONHOMME. 1992. Modelling radiative transfer in mixed and row intercropping systems. *Agric. For. Meteorol.* **62**: 219-240.

THANISAWANYANGKURA, S., H. SINOQUET, P. RIVET, M. CRETENET and E. JALLAS. 1997. Leaf orientation and sunlit leaf area distribution in cotton. *Agric. For. Meteorol.* **86**: 1-15.

TOURNEBIZE, R. and H. SINOQUET. 1995. Light interception and partitioning in a shrub/grass mixture. *Agric. For. Meteorol. 72:* 277-294.

VATTI, B.R. 1992. A generic solution to polygon clipping. *Commun. ACM.* **35**: 56-63.

WALLACE, J.S. 1997. Evaporation and radiation interception by neighbouring plants. *Q.J.R. Meteorol. Soc.* **123:** 1885-1905.