Deriving Spatial Inputs for Forest Microclimate Modelling Using Remote Sensing Techniques

Zulkiflee Abd Latif, *Member, IEEE and* George Alan Blackburn

***Abstract*— The creation of gaps in forest canopies can dramatically change the microclimate and soil water balance which strongly influences the process of regeneration and biodiversity within forest ecosystems. Hence, understanding the microclimatic conditions in canopy gaps is a prerequisite in developing and improving techniques for forest management and conservation practices. However, information is scarce on how the size and shape of gaps and their spatial distribution affects the microclimate and soil water balance across forest stands. In the present study we investigated the potential for retrieving forest gap and canopy attributes from LiDAR and multispectral sensors in order to provide new opportunities for modelling forest microclimates. A spatially explicit microclimate model (FORGAP-BD) was developed which could be driven using spatial inputs from remote sensing. The model was implemented for a study site in the broadleaved deciduous forest, Eaves Wood, UK in order to quantify the spatio-temporal dynamics of microclimates over an entire forest stand.**

***Index Terms*— LiDAR, multispectral, microclimate, FORGAP-BD, spatial**

I. INTRODUCTION

Forests are crucial to the well being of humanity; they provide foundations for life on Earth through ecological functions, by regulating the climate and water resources, and by serving as habitats for plants and animals. In temperate forests wind throw often creates canopy gaps which can dramatically change the microclimate and soil water balance [1,2,11]. Hence, understanding the microclimate conditions in canopy gaps is a prerequisite in developing and improving techniques for forest management and conservation practices. Fig. 1 demonstrates the nature of these changes, in general terms. However, information is scarce on how precisely gap size and shape affects the microclimates within canopy gaps and beneath surrounding tree canopies and how the spatial distribution of gaps influences microclimates across entire forest stands [2].

Remote sensing is increasingly seen as an important tool for providing information to achieve sustainable and efficient forest management. The past decade has seen growing interest in the use of remote sensing technologies in forest studies. In particular Light Detection and Ranging (LiDAR) devices together with new analytical techniques allow increasingly detailed information to be derived for forests. LiDAR systems offer an alternative to *in situ* field surveys and photogrammetric techniques for the collection of elevation data. LiDAR provides accurate, timely data, is capable of operating in difficult terrain and is increasingly affordable. LiDAR technology is becoming capable of providing 3-dimensional information at high spatial resolutions and vertical accuracies [5]. Forest attributes such as crown heights and individual canopy gap delineations can be directly retrieved from LiDAR data [11] while tree species classifications may be derived from multispectral imagery [4]. Thus, with high spatial resolution remotely sensed imagery, the spatial properties and composition of tree canopies and gaps can be obtained over large areas. With the capabilities of direct retrieval of forest attributes

Manuscript received January 17, 2011. This work was supported in part by the UK NERC ARSF under Grant GB08-15, Lancaster Enviroment Centre, UK, UK NERC GEF, Ministry of Higher Education, Malaysia and UK National Trust.

Dr. Zulkiflee Abd Latif is currently with the Centre for Geospatial Technology, Faculty of Architecture, Planning & Surveying, University of Technology MARA, Shah Alam, 40450 Selangor Malaysia (phone: +603-55444399; fax: +603-55444545; e-mail: zulki721@ salam.uitm.edu.my).

Dr. Alan Blackburn is with Lancaster Environment Centre, Lancaster, UK. (phone: +603-55444399; fax: +603-55444545; e-mail: zulki721@ salam.uitm.edu.my).

offered by remote sensing, this provides new opportunities to model forest gap microclimates. By developing an inherently spatial microclimate model and driving this with inputs from remote sensing we have the potential to quantify forest gap microclimates over entire forest stands. This study aims to examine the feasibility of such an approach using a case study of a broadleaved deciduous forest in the UK.

II. STUDY SITE AND DATA COLLECTION

The study site was Eaves Wood, Silverdale (2° 49'W, 54° 10'N), northern England, which covered an area of 50.6 ha.

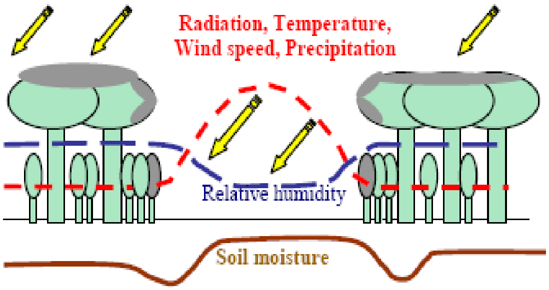


Fig. 1. Gradients of microclimate conditions and soil moisture in forest canopy gaps. The areas on the vegetation represent the parts of the crowns that can receive direct solar radiation.

The area is a mixed semi-natural deciduous forest and designated as an Area of Outstanding Natural Beauty and a Site of Special Scientific Interest. Dominant tree species are oak (*Quercus petraea)* and beech (*Fagus Sylvatica).* LiDAR data were acquired by the UK National Environment Research Council Airborne Research Survey Facililty (NERC ARSF) aircraft using Optech Airborne Laser Terrain Mapping (ALTM) 3033, in May 2008. The altitude of the aircraft was 900 m above ground level and a swath width of approximately 600 m was surveyed along each flight line. Imagery of the study site was also acquired using a Daedalus Airborne Thematic Mapper (ATM). The aircraft altitude was 670 m (2200 ft) which generated imagery with a spatial resolution of 1 m. The ATM instrument acquired imagery in 12 wavebands across the visible, near-infrared and short-wave infrared.

III. EXTRACTION OF GAP AND CANOPY PROPERTIES

A key determinant of forest microclimate, as described in the FORest GAP-Broadleaved Deciduous (FORGAP– BD) model is the receipt of solar radiation, which can be direct or transmitted through the canopy and therefore varies considerably both spatially and temporally. Hence, an important part of the project was to extract from remotely-sensed data those canopy variables that could be used to quantify the radiation regime within gaps and at the forest floor.

A. Canopy extinction coefficient via tree species classification

The attenuation of radiation by a tree canopy is quantified in the FORGAP-BD model as the product of the extinction coefficient and the leaf area index of the tree. The extinction coefficient depends on the canopy architecture and leaf angle distribution which is species dependent [7]. Hence, supervised training and a maximum likelihood decision rule were used to classify the ATM data in order to generate a species map.

Samples were taken randomly within the cluster of all vegetation types in the study area. This was considered as the most cost effective method. As to the size of the sample for each class, a minimum of 50-100 pixels is recommended by the majority of research community [8]. In the present study, 94 GPS points were used to classify the trees throughout the study area. At each sampling location a real time differential GPS (Leica System 500 with RTK) receiver with sub-metre horizontal accuracy was used to provide positional information (Fig. 2). The GPS was positioned under or at the edge of the tree crown (depending on the positional accuracy) and the tree species at this and neighbouring positions was recorded. In the rectified image (same reference map as GPS points), whole crowns of the trees in the specific position and its neighbourhood were taken as the sample. As tree of the same species often differ in appearance in semi-natural woodland, samples of each category especially beech and oak were taken from scattered points to ensure as accurate representation as possible. Similarly, 104 points were measured using the same procedures in order to assess the accuracy of the classified ATM.

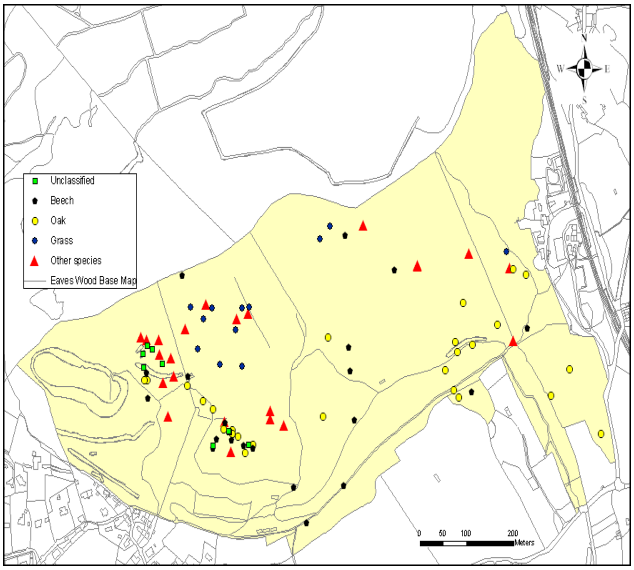


Fig. 2. Sampling points for tree species classifications using DGPS.

For the purpose of this study, region of interest (ROIs) within the forest stand maps of the National Trust were used as guides to extract spectral signatures for each class. Since the aim of this study involves the classification of forest broadleaved deciduous species, sampling of training sites were based on the distribution of these targets. Five training classes (including bare/gap areas, oak, beech, other tree species and grass) were chosen in equivalent to the five land cover classifications that was initially determined for the purpose of forest microclimate modelling in the study area. Furthermore, each of these five classes will be assigned radiation extinction coefficients and driving these inputs into the FORGAP-BD model. Radiation extinction coefficients assigned to each classified tree species based on the values extinction coefficient (*k*) for broadleaved stands found in [3] (see Table 1).

TABLE 1

VALUES OF EXTINCTION COEFFICIENT FOR GLOBAL RADIATIONMEASURED IN BROADLEAVED STANDS.

Broadleaved stands	k
Grass	0.5
Fagus Sylvatica (Beech)	0.43
Mixed broadleaved (Other species)	0.50
Quercus petraea (Oak)	0.3

B. Derivation of leaf area index

Leaf area index (LAI) is the second parameter required to quantify the interception of solar radiation by the tree canopy. A number of vegetation indices were derived from the original 12 spectral bands of the ATM. Through comparison with measurements of LAI made *in situ* using an LAI-2000 instrument (Fig. 3) it was found that a simple ratio (using the NIR (band 7) and green (band3)) was a suitable predictor of LAI across the study site.

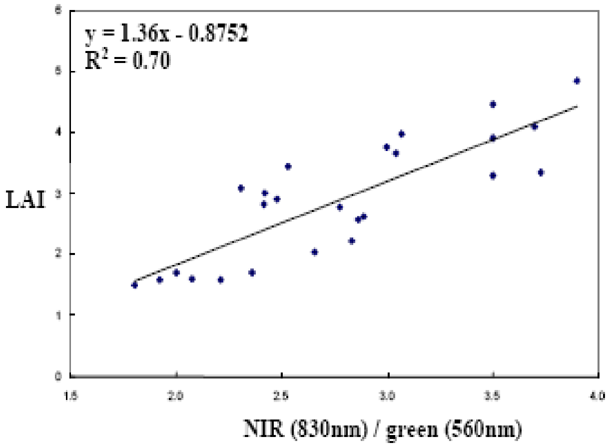


Fig. 3. Relationship between LAI (measured *in* situ) and the simple ratio of NIR (830 nm)/green (560 nm) reflectance (ATM bands 7/3) for the broad-leaved stands

C. Gap delineation and canopy height model

A possible approach for discriminating gaps from canopy areas would be to use a thresholding procedure based on the brightness of the pixels in the ATM imagery. However, this was found to be unsuitable because of the spectral variability introduced by scene components such as sunlit and shaded parts of tree crowns and gaps [10,5]. Hence, in order to overcome the difficulties associated with spectral variability a masking approach based on the LiDAR data was developed.

Gap identification from LiDAR imagery was performed using Erdas Imagine (v.9.1) and ArcGIS (v.9.2) software. Canopy heights were derived from LiDAR data; however an estimate of the ground elevation was needed. A digital terrain model (DTM) was constructed from elevation data provided by the U.K. Ordnance Survey (OS). The OS DTM was calibrated against the LiDAR last return point clouds of bare soils and road surfaces. A canopy height model (CHM) was calculated as the difference between elevation values in the LiDAR data and ground elevation at corresponding locations. Based on the field visits, it was determined that the height below which areas would be identified as gaps should be between 2m and 5 m. Thus, the height of 4 m was therefore selected as the threshold for distinguishing canopy from gap areas. From the CHM all grid cells with a height less than or equal to 4 m were assigned as gap areas.

D. Forest microclimate modelling

A spatially explicit model of forest gap microclimates and soil water balance was developed based on previous reviewed literatures and field measurements of microclimates and soil water balance [13]. FORGAP-BD model is written in the dynamic script modelling language PcRaster [8] and comprises two sub-modules, radiation and soil water balance. The radiation module calculates the potential radiation on the vegetation, the potential radiation on the saplings in the gap and area surrounding the gap and the potential radiation on the soil. The second sub module calculates the soil moisture content at 5cm depth both within gaps and beneath the forest canopy. FORGAP-BD was developed to be driven by a set of spatial inputs derived from remote sensing (canopy height, gap map and LAI) together with a DEM and meteorological data from a nearby weather station (Fig. 4). In order to refine the model, future work will concentrate on validation using ground-based micrometeorological measurements.

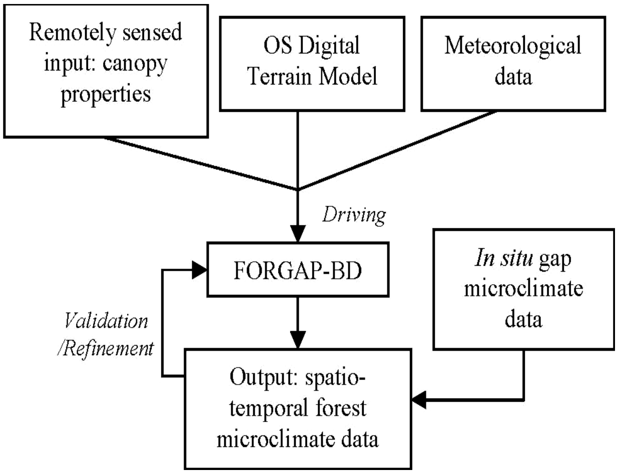


Fig. 4. Methodological framework of the integration of remotely sensed and meteorological data into the FORGAP-BD model.

IV. ACCURACY ASSESSMENT

The thematic maps produced by classification methods are subjected to errors. An assessment on the accuracy of each classification is required in order to estimate the magnitude of these errors. Accuracy describes the closeness of a measurement to the true value of the quantity being measured. The accuracy assessment procedure is conducted by comparing the information from the classified map with the corresponding information on the reference map or information collected in the field. The standard method used to report classification errors is through the use of an error matrix, often known as confusion matrix. A confusion matrix is a square tray set out in rows and columns which expresses the number of sample units assigned to a particular class or category relative to the actual class as verified by ground reference data. In this study, the accuracy of the classification using unsupervised and supervised classifier is based on the computation and analysis of this confusion matrix.

A confusion matrix allows the assessment classification accuracy to be carried out both descriptively and analytically. An overall accuracy is computed by dividing the total number of pixels classified correctly by the total number of pixels forming the test data set. The diagonal elements of the confusion matrix represent the pixels in all reference classes. The overall accuracy can be expressed as producer's accuracy or user's accuracy. The producer's accuracy is based on the reference data (columns) and it is the probability of misclassifying a pixel belonging to a given class, resulting in omission errors. Conversely, the user's accuracy is based on the total number classified in specific (rows) classes, in which a pixel is assigned erroneously to a given class, resulting in commission errors. It is insufficient to rely on the overall accuracy value alone, especially when accessing product of classification method. An analytical approach using multivariate statistical techniques is also useful. A widely used multivariate technique for accuracy assessment of classification output is Kappa analysis. The kappa coefficient measures the randomness of the results by computing the difference between the actual agreement in the confusion matrix against the probable agreement as indicated through the sum of rows of columns of the matrix.The kappa coefficient is calculated from the following equation [1]:

$$K = \frac{n\sum_{i=1}^{p} x_{ii} - \sum_{i=1}^{p} x_{io}x_{oi}}{n^2 \quad \sum_{i=1}^{p} x_{io}x_{oi}} \qquad (1)$$

where n :total number of pixels used for testing the accuracy of a classifier

p : number of classes

Σx_{ii} : sum of diagonal elements of confusion matrix

Σx_{io} : sum of row i

Σx_{oi} : sum of column i

V. RESULTS AND DISCUSSION

A. *Map of tree species*

A map of the dominant deciduous tree species (oak and beech) was produced from supervised classification of the ATM data with an assessed accuracy of 75% (Kappa = 0.67) (see Fig. 5). Oak covers 15% of the area and beech 10%. Other sub-dominant species (e.g. birch, hazel, yew and pine) cover 67 % of the total area, with the remaining 8% being gaps.

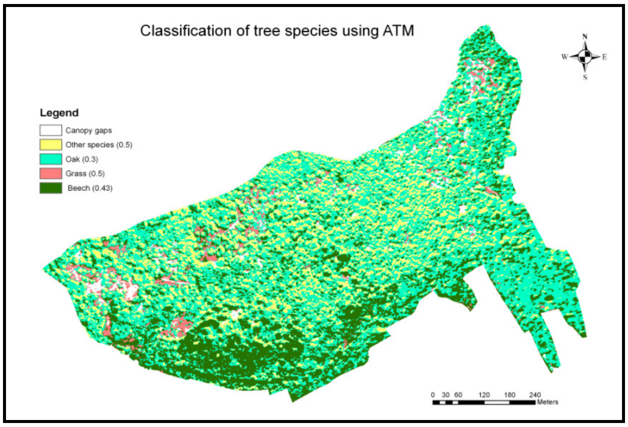


Fig. 5. Map of tree species and associated extinction coefficients based on classified ATM data

B. *Derivation of Leaf Area Index*

An examination of the accuracy of the LAI map as measured by the RMSE from cross-validation confirmed that the use of ATM imagery to estimate LAI spatially is valid. There was a strong relationship between predicted and measured LAI (R^2 = 0.82; Fig. 6.(a), an RMSE of 0.28. This result is in agreement with previous study by [3] which defined SR using NIR and green bands as a best LAI estimator for broadleaved deciduous woodlands.

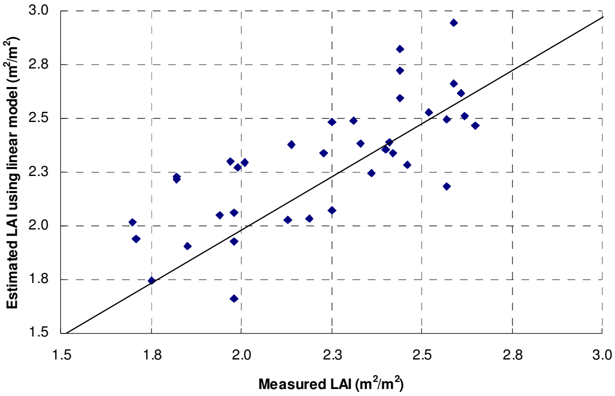


Fig. 6 (a). LAI estimated using SR (NIR/Green) versus measured LAI ($P < 0.05$).

Fig. 6 (b) shows LAI map derived from the ATM data using the relationship between Simple Ratio (SR) and in-situ LAI. The calculated root mean square error (RMSE) between the in-situ and the predicted LAI was 0.280 (R_2 = 0.82).

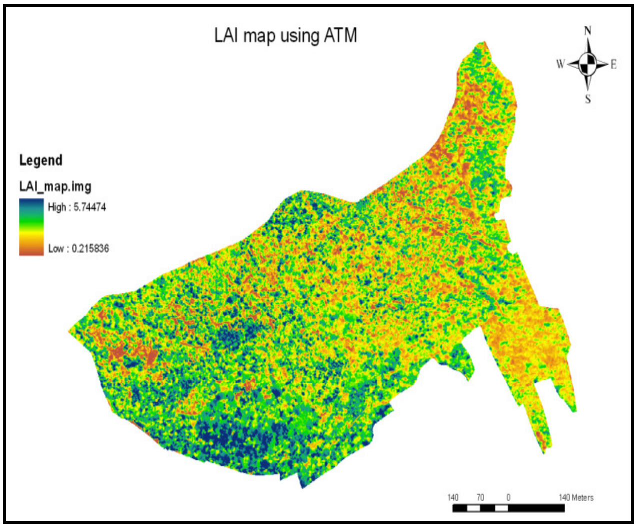


Fig. 6(b). LAI map of Eaves Wood derived using ATM data.

B. *Maps of tree height and canopy gaps*

Map of tree height as estimated from CHM using LiDAR shown in Fig. 7 while gap areas extracted from the LiDAR data are shown in Fig. 8. An accuracy assessment using 90 ground-based control points revealed a root mean squared error (RMSE) of 0.48 m for the DTM and an RMSE of 0.82 m for the canopy surface height image.

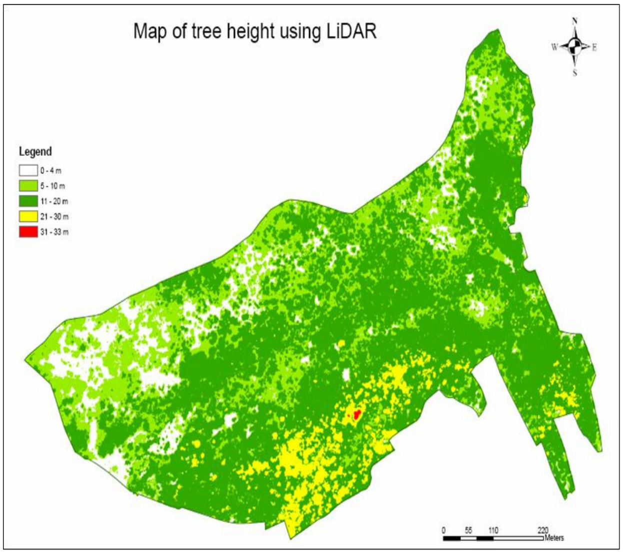


Fig. 7. Map of tree height estimated from the LiDAR CHM.

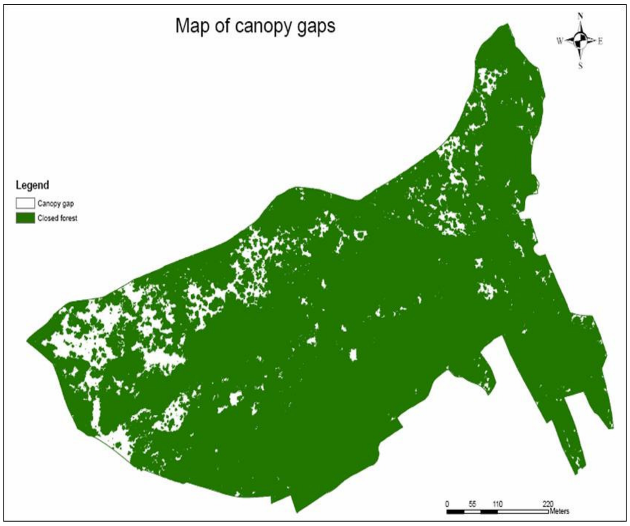


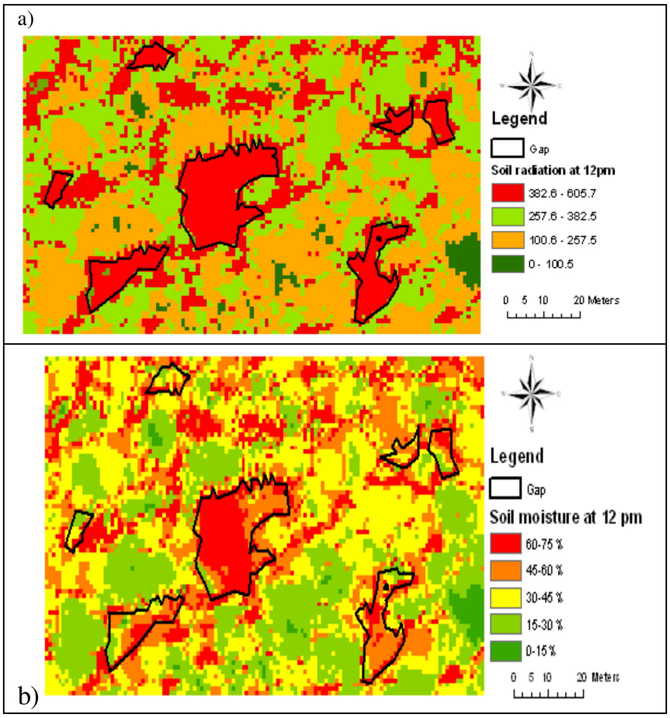
Fig. 8. Map of canopy gaps from derived from the LiDAR data.

D. *FORGAP-BD outputs*

The spatial data above were used to drive the FORGAP-BD model in order to generate both spatial and temporal simulations of forest microclimates. In order to demonstrate the output from the FORGAP-BD model, fig. 9 shows spatial outputs from FORGAP-BD for a specific time point (solar noon), which illustrates the detailed information concerning microclimate that the model is able to generate. Fig. 9 shows diurnal time series of solar radiation, air temperature and relative humidity for a specific location at the centre of as well as a location beneath the adjacent forest canopy (Julian day : 200).

The diurnal changes in solar radiation, air temperature, relative humidity and wind speed as simulated by FORGAP-BD for the centre of a selected gap and beneath the adjacent forest canopy are shown in Fig.10.

Total solar radiation at 12 noon on Julian day 200 was 713 W.m^{-2} in the gap and 521 W.m^{-2} beneath the adjacent canopy. At 12 noon, air temperature was 30.9˚C at the gap centre and 27.4˚C in the sub-canopy. Wind speed was found to be considerably higher in the gap as compared to the sub-canopy. However, relative humidity values were lower in the gap than the forest during mid day. Hence, all the microclimate variables calculated using the FORGAP-BD model were as expected.



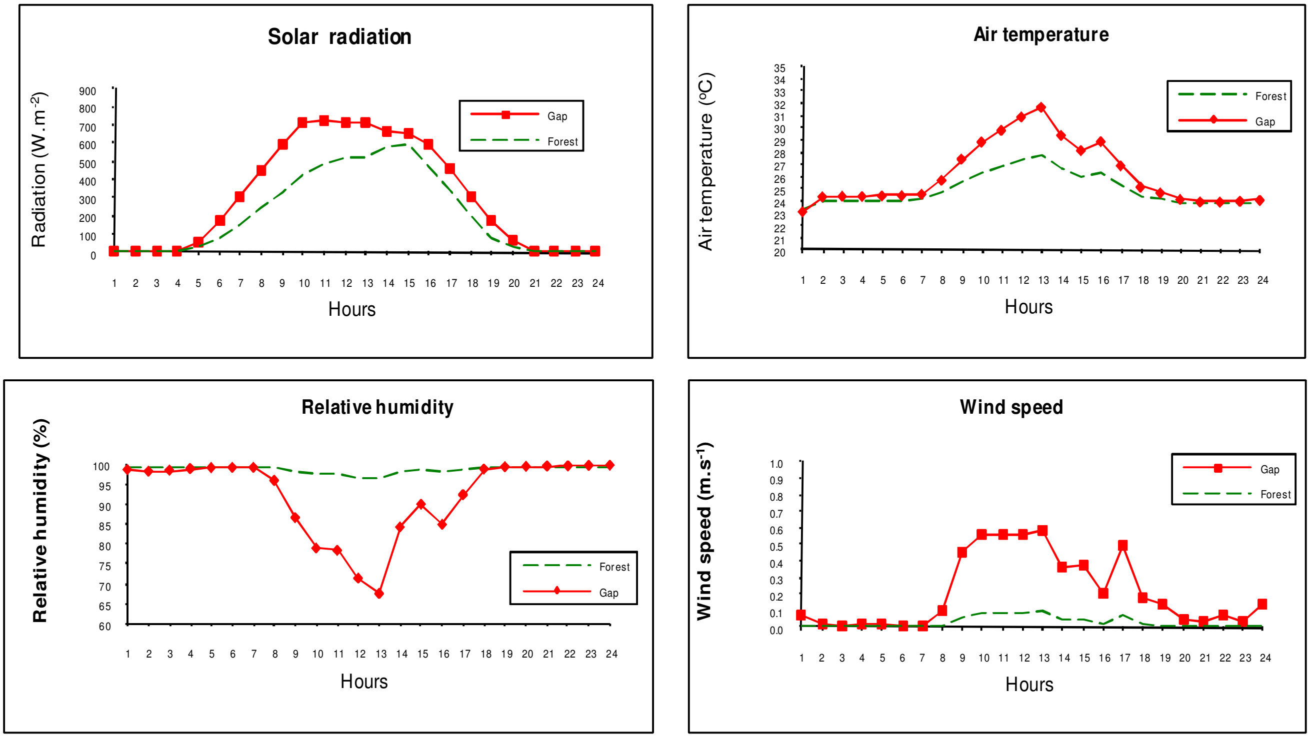


Fig.10. FORGAP-BD outputs showing the diurnal patterns of total solar radiation, air temperature, wind speed and relative humidity at a selected gap centre and beneath the adjacent forest canopy on Julian day 200.

VI. CONCLUSION

This study has demonstrated that it is possible to extract gap and canopy properties from LiDAR and multispectral data in order to generate spatial inputs for forest gap microclimate modelling. The use of remote sensing greatly reduces the time and fieldwork effort required and can provide a comprehensive set of spatial information that is difficult to obtain using traditional methods.Remote sensing provides an increasing variety of spatial data layers that are potentially useable as model input. This study has demonstrated that it is possible to develop a simulation model using gap and canopy data derived from remote sensing in order to generate spatial and temporal estimates of microclimate. Further work will focus on improving the methods for delineating gaps and extracting canopy properties from LiDAR and hyperspectral data, driving the model using a seasonal time series of gap and canopy variables and evaluating the impact of these techniques on the accuracy of microclimate model outputs.

VII. ACKNOWLEDGMENT

The authors would like to thank the UK NERC ARSF for providing ATM and LiDAR imagery, the Research Committee, Lancaster University and NERC GEF for equipments, Ministry of Higher Education, Malaysia for providing research funding and the National Trust for giving access to Eaves Wood as study site.

REFERENCES

[1] Abdul Hamid, J. R., Mapping of Forest Using Imaging Spectrometry and LiDAR Data. *Dissertation*. Department of Geography. University of Nottingham, U.K, 2005.

[2] Abd Latif, Z., and G.A. Blackburn, *The effects of gap size on some microclimate variables during late summer and autumn in a temperate broadleaved deciduous forest.* International Journal of Biometeorology. Vol 54: pp. 119-129, 2010.

[3] Blackburn, G.A, *Remote sensing of forest pigments using airborne imaging spectrometer and LIDAR imagery.* Remote Sensing of Environment. Vol **82**: pp. 311-321, 2002.

[4] Breda, N., Soudani, K. & Bergonzini, J. C. *Mesure de l'indice foliaire en foret,* Paris, Ecofor, 2002.

[5] Lucieer, A., A. Stein, and P. Fisher, *Multivariate texture-based segmentation of remotely sensed imagery for extraction of objects and their uncertainty.* International Journal of Remote Sensing. Vol 26(14): pp. 2917-2936. 2005

[6] Abdul Hamid, J. R., Mapping of Forest Using Imaging Spectrometry and LiDAR Data. *Dissertation*. Department of Geography. University of Nottingham, U.K, 2005.

[7] Abd Latif, Z., and G.A. Blackburn, *The effects of gap size on some microclimate variables during late summer and autumn in a temperate broadleaved deciduous forest.* International Journal of Biometeorology. Vol 54: pp. 119-129, 2010.

[8] Blackburn, G.A, *Remote sensing of forest pigments using airborne imaging spectrometer and LIDAR imagery.* Remote Sensing of Environment. Vol **82**: pp. 311-321, 2002.

[9] Breda, N., Soudani, K. & Bergonzini, J. C. *Mesure de l'indice foliaire en foret,* Paris, Ecofor, 2002.

[10] Lucieer, A., A. Stein, and P. Fisher, *Multivariate texture-based segmentation of remotely sensed imagery for extraction of objects and their uncertainty.* International Journal of Remote Sensing. Vol 26(14): pp. 2917-2936. 2005

[11] Lee, A.C. and R.M. Lucas, *A LiDAR-derived canopy density model for tree stem mapping in Australian forests.* Remote Sensing of Environment. Vol **111**: pp. 493-518, 2007.

[12] Smith, F.W., A.D. Sampson, and N.J. Long, *Comparison of leaf area index estimates from tree allometrics and measured light interception.* Forest Science. Vol **37**: pp. 1682 -1688, 1991.

[13] PCRaster, *PCRaster manual.* Department of Physical Geography, Utrecht University, Netherlands, 1995.

[14] Mather, P.M., *Computer processing of remotely sensed images: An Introduction.* Wiley, Chichester, 1989.

[15] Koukoulas, S., *Analysing the spatial structure of semi-natural deciduous woodlands through high resolution airborne imagery and Geographical information system.* PhD thesis, Department of Geography, Kings College, University of London, UK, 2001.

[16] Koukoulas, S. and G.A. Blackburn, *Spatial relationships between tree species and gap characteristics in broad-leaved deciduous woodland.* Journal of Vegetation Science, Vol. **16**: pp. 587-596, 2005.

[17] Yamamoto S. I., *Gap characteristics and gap regeneration in a subalpine old-growth coniferous forests, central Japan.* Ecological Research, vol. 10, pp.31-39, 1995.

[18] Van Dam, O., *Forest filled with gaps: the effects of gap size on microclimate, water and nutrient cycling. A study in Guyana.* PhD thesis.. Uthrect University, Netherlands, 2001

[19] Abdul Hamid, J. R., Mapping of Forest Using Imaging Spectrometry and LiDAR Data. *Dissertation*. Department of Geography. University of Nottingham, U.K, 2005.

[20] Abd Latif, Z., and G.A. Blackburn, *The effects of gap size on some microclimate variables during late summer and autumn in a temperate broadleaved deciduous forest.* International Journal of Biometeorology. Vol 54: pp. 119-129, 2010.

[21] Blackburn, G.A, *Remote sensing of forest pigments using airborne imaging spectrometer and LIDAR imagery.* Remote Sensing of Environment. Vol **82**: pp. 311-321, 2002.

[22] Breda, N., Soudani, K. & Bergonzini, J. C. *Mesure de l'indice foliaire en foret,* Paris, Ecofor, 2002.

[23] Lucieer, A., A. Stein, and P. Fisher, *Multivariate texture-based segmentation of remotely sensed imagery for extraction of objects and their uncertainty.* International Journal of Remote Sensing. Vol 26(14): pp. 2917-2936.

2005

[24] Lee, A.C. and R.M. Lucas, *A LiDAR-derived canopy density model for tree stem mapping in Australian forests*. Remote Sensing of Environment. Vol **111**: pp. 493-518, 2007.

[25] Smith, F.W., A.D. Sampson, and N.J. Long, *Comparison of leaf area index estimates from tree allometrics and measured light interception.* Forest Science. Vol **37**: pp. 1682 -1688, 1991.

[26] PCRaster, *PCRaster manual.* Department of Physical Geography, Utrecht University, Netherlands, 1995.

[27] Mather, P.M., *Computer processing of remotely sensed images: An Introduction*. Wiley, Chichester, 1989.

[28] Koukoulas, S., *Analysing the spatial structure of semi-natural deciduous woodlands through high resolution airborne imagery and Geographical information system*. PhD thesis, Department of Geography, Kings College, University of London, UK, 2001.

[29] Koukoulas, S. and G.A. Blackburn, *Spatial relationships between tree species and gap characteristics in broad-leaved deciduous woodland.* Journal of Vegetation Science, Vol. **16**: pp. 587-596, 2005.

[30] Yamamoto S. I., *Gap characteristics and gap regeneration in a subalpine old-growth coniferous forests, central Japan*. Ecological Research, vol. 10, pp.31-39, 1995.

[31] Van Dam, O., *Forest filled with gaps: the effects of gap size on microclimate, water and nutrient cycling. A study in Guyana.* PhD thesis.. Uthrect University, Netherlands, 2001

Zulkiflee Abd Latif (M' 10) received his Ph.D. in remote sensing from Lancaster University, UK in 2010. He is a senior lecturer at FSPU, UiTM, Malaysia. He is currently an associate researcher at Centre for Geospatial Technology, FSPU, UiTM. His research interests include environmental modeling with remotely sensed data and laser scanning applications.

Dr. Zulkiflee is a member of Institute of Surveyors, Malaysia and RSPSoc UK.

George Alan Blackburn received his Ph.D. in remote sensing from University of Southampton, UK in 1993. He is a lecturer at Lancaster Environment Centre, Lancaster, UK. His research focuses on developing remote sensing and GIS techniques for environmental applications, particularly in ecology and biodiversity, vegetation physiology and dynamics and environmental security.

Dr. Blackburn is a member of RSPSoc UK and ISPRS.