academicJournals

Vol. 5(4), pp. 53-60, May 2013
DOI 10.5897/JHF2013.001
ISSN 2006-9782 © 2013 Academic Journals
http://www.academicjournals.org/JHF

Journal of Horticulture and Forestry

Full Length Research Paper

Improved model for estimation of leaf area index using airborne laser profiling

John N. Kigomo[1]*, Tatsuo Sweda[2] and Hayato Tsuzuki[2]

[1]Kenya Forestry Research Institute, P. O. Box 20412-00200, Nairobi, Kenya.
[2]Faculty of Agriculture, Ehime University, Matsuyama, Ehime 790-8566, Japan.

Accepted 13 May 2013

The study was conducted to derive a functional relationship between airborne laser generated forest profile area and ground-based leaf area index (LAI) for extensive estimation. Subsequently, LAI was estimated by applying parameterized derived equations to the laser data covering a 384 ha temperate forest in Ehime, Japan. There is a growing demand for accurate estimates of LAI in larger areas due to its role in monitoring climate change and forest productivity. However, due to complicated nature of terrestrial vegetation and rapid land use changes, accurate and precise estimation of LAI has been a challenge. Although, the functional relationship of laser-generated profile area (*S*) and forest biomass (*W*) is well established, the relationship with LAI is still at infancy. In this research, a function relating LAI and *S* was derived with an improved estimation of LAI, RMSE = 1.32 and Bias = 0.21. Our results showed reasonable agreement between Laser estimated and field derived LAI, r = 0.6 (p = 0.014). This study covered a small area and validation of the findings in larger scale could be recommended.

Key words: Airborne laser altimetry (ALA), leaf area index (LAI), forest profile area, climate change, remote sensing.

INTRODUCTION

Leaf area index (LAI) defined as one-half of the total leaf area per unit ground surface area (Fournier et al., 2003) is an important canopy variable needed for many physiological and ecosystem studies. It has been related to canopy interception, transpiration, net photosynthesis and net primary productivity (Pierce and Running, 1988; Gower and Norman, 1991). The ability to rely on a measurable variable that will remain consistent from one scale to another is important in regional as well as in global scale assessment and monitoring (Enquist and Niklas, 2001). In this point of view, LAI is a convenient and ecologically relevant variable for multi-scale estimations that range from leaf to region. Accurate estimations of leaf area over extensive areas are crucial in land surface schemes for climate models (Sitch et al., 2008; Stockli et al., 2008), and models of global phenology (Kang et al., 2003; Arora and Boer, 2005). Furthermore, demands for accurate estimations of LAI at regional, national and even global levels are increasing after being recognized as a vital boundary input in global circulation models (GCM) for projection of global warming.

The ability to measure accurately and precisely structural and functional changes of forest ecosystems in time and space, is increasingly gaining global attention, recognizing the forest role in regulation of global atmospheric changes. However, due to complicated nature of terrestrial vegetation and rapid land use changes, accurate and extensive assessment of forest are rather cumbersome, time consuming and expensive when using conventional forest methods. As the need for quantity and quality of information increases, remote

*Corresponding author. E-mail: kigomo2@yahoo.com. Tel: +254735393821.

sensing becomes a powerful tool in forest planning and management. Satellite data have been used to estimate LAI based on relationships between remote sensing data and LAI field measurements. The vegetation indices, derived from satellite images, have been significantly correlated to LAI for a wide range of forest types (Spanner et al., 1994; Fassnacht et al., 1997; Wulder et al., 1998). However, regardless of improvement of spatial and spectral resolutions, the inability of spectral imagery to characterize adequately the vertical structure of forest canopies is still a limitation in application of this technology (Hall et al., 1996; Hasegawa et al., 2006).

Therefore, to bridge the gaps, the use of airborne laser altimetry (ALA), which provide three dimensional information of forest characteristics, has increased rapidly in past few decades (Lefsky and Cohen, 2003). Laser altimetry operates by measuring the vertical profile in vast areas through converting lapsed time between emitted pulses from laser altimeters and returning signals from the target objects, whether vegetation or ground surfaces. Laser technology can directly measure the vertical distribution of tree canopies and provide highly accurate forest profile height and structure. Consequently, standing stock and biomass has been derived (Nelson et al., 2004; Lefsky et al., 2001). Kusakabe et al. (2000) tried the indirect estimation of LAI in extensive boreal forests through correlation of LAI with standing stock and not directly with laser derived estimations. Strong correlation between ground measured timber stock and laser estimations has been achieved in the temperate forest of Japan (Tsuzuki et al., 2008; Ioki et al., 2010).

However, studies on relationship of LAI with laser metrics in temperate and tropical forests are not available. The aim of this study was to establish the theoretical relationships between LAI and laser metrics, and to estimate the LAI of one particular forest, Ehime University Experimental Forest, Japan.

MATERIALS AND METHODS

Study site and laser profiling

The study was conducted in a 384 ha secondary temperate forest with an altitude ranging from 500 to 1200 m above sea level. The dominant tree species are *Cryptomeria japonica* (sugi), *Chamaecyparis obtusa* (hinoki) and mixed deciduous and evergreen broadleaf tree species. The laser data used for this study was obtained in September 2005, using NASA's portable airborne laser systems (PALS). PALS operation technology (Nelson et al., 2003) was designed to collect forest profile measurements along linear flight transect in extensive (landscape) areas beyond plot and stand levels. In the aforementioned mission, a helicopter fitted with PALS was flown about 200 m above ground, at a nominal cruising speed of 180 km/hr, with an alternating first/last pulse altimetry data retrieval frequency of 400 Hz. This translates to a nominal horizontal measurement of about 0.13 m along the flight track. Seven North to South laser transects of about 4000 m long, and approximately 250 m apart, were obtained.

The main output of ALA was three dimensional data; latitude (°N), longitude (°E) and elevation (m). They were converted to comma separated values (csv) in MS-Excel, and later to keyhole markup language (KML) file format through csv2kml.exe software, aiming at achieving seven laser lines in Google earth. Since the primary data included reflections from canopy and ground surfaces, that is, first and last laser return, a continuous ground profile was obtained by fitting cubic spline interpolation curve of suspended topographic surface reflections using JMP v. 9 statistical software.

Thereafter, topographic profile was subtracted from canopy surface profile to get the forest/vegetation profile after calibration with ground measured LAI (Figure 1). A series of ground surveys were conducted along the flight paths in model development, aiming at correlating the vegetation profile with actual LAI.

Ground survey

We viewed video tape movie recorded during laser profiling mission in order to have an in-depth overview of vegetation and topography of the study area. Locations of tie-in-points (TIPs) were identified to assist in accessibility and location of plots. Such points included logging roads, ridges, rivers and other land marks which were conspicuously visible. Laser line two, four and six were selected and compared with video tape movie for possible location of plots along the lines. The three lines were selected because they were representative in terms of stand age, species type and range of altitude within the study area. Factors such as type of species, vegetation profile height and accessibility were considered when locating sample plots. Video print-outs were prepared for all necessary TIP's to guide during actual data collection.

Flight path direction and bearing were determined through generating laser lines in a simple scatter smooth lines graph, with eastings on the x-axis and northing's on the y-axis. With an estimated 1°C change in northing's being equivalent to 112 km (considering the radius of the earth about 6,415 km); we calculated distance and bearings of all the sections of interest which corresponded with preliminary plot locations. Using a hand-held global positioning system (GPS), topographical map of 1: 25,000 scale, a compass corrected for magnetic declination of 6.5°C for Matsuyama region and other materials prepared as aforementioned, flight path navigation was carried out to locate plots. We determined topographical slope angle and ground distance using vertex laser. Stand boundaries and species composition were also determined during the mission. After the navigation exercise, a total of nineteen plots (nine plots for broad leaved, six plots for *C. japonica* and four representing *C. obtusa*) were selected for data collection.

Non-fixed sample plots were established through measuring height of three randomly selected trees in each of the proposed nineteen plots. Arithmetic mean of the sample tree heights was squared and plot area approximately equal to squared mean stand height was established. Strip plots were preferred since laser profiling data was collected in a linear flight transect. After plot demarcation, GPS points were taken at the center of plot widths and diameter at breast height (dbh) of all trees above a dbh of 5 cm was measured.

Using dbh data of trees measured in the sample plots as a guide of representative sizes of trees, twenty two trees, including *C. japonica* (6), *C. obtusa* (8) and mixed broad leaf species (8), were selected for destructive sampling within the study areas. Before felling, dbh was measured. After felling, determination of leaf areas of broad leaf species and *C. obtusa* was carried out through detaching leaves from branches and twigs and weighing fresh weight. A sub-sample of leaves about 200 g was randomly collected and weighed. The leaves were then scanned with canon scan Lide 600 F as graphic images and leaf area analyzed using Image J, a public domain Java-based image processing developed

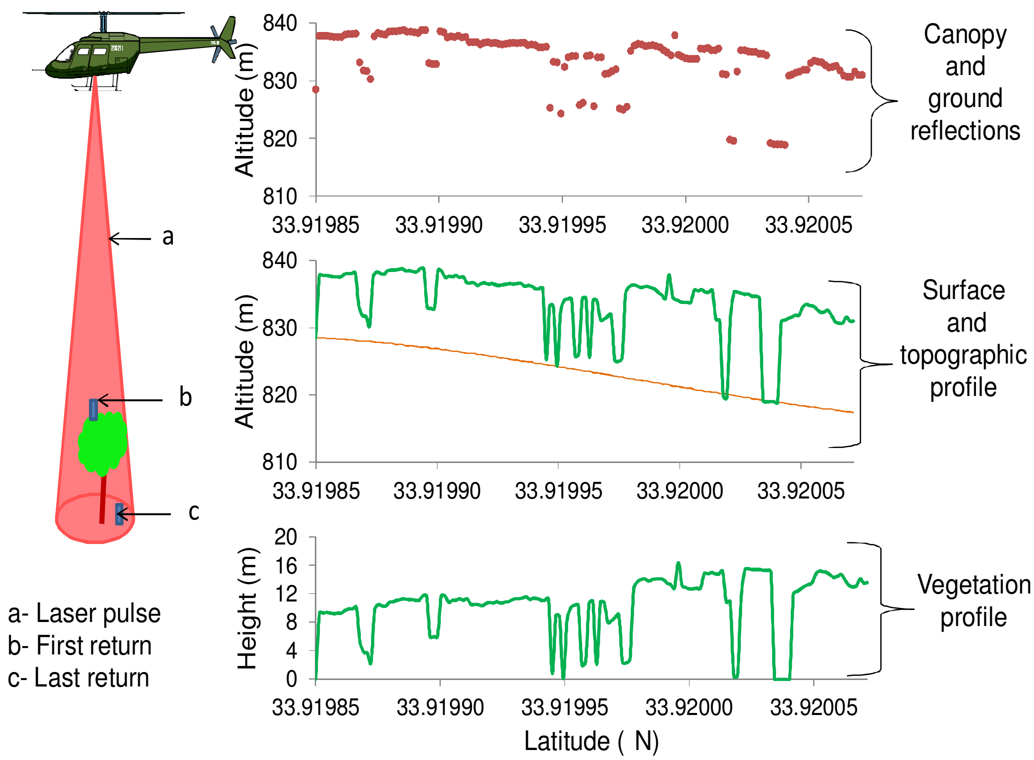

Figure 1. Illustration of airborne laser profiling and processing of vegetation profile; Main components in Portable Airborne Laser Systems fitted in aircraft include Infrared Laser Altimeter (ILA), Video Tape Recorder (VTR) and Differential GPS.

in the National Institute of Health, USA. The ratio of leaf area to sub-sample fresh weight was used to estimate leaf area of individual tree from total fresh weight of leaves. Allometric equation was formed by regressing sample tree's dbh to leaf area as shown in Figure 2, with parameters fitted through nonlinear least square method (Equation 1);

$$y = a(dbh)^b \tag{1}$$

where y is leaf area, a and b were parameters fitted by ground based measures of leaf area (Shinozaki et al., 1964; Gregoire et al., 1995; Turner et al., 2000). The parameterized Equation 1 was then used to estimate total plot leaf area using measured stem's dbh in each plot. LAI was then obtained as a ratio of the total one-side leaf area in the plot to the ground plot area.

Due to morphological differences of *C. japonica* leaves (needles) from the other tree species, a different approach was used to measure projected area instead of one-side leaf area. Sample tree's dbh ranged from 7.0 to 39.0 cm. After felling, total height and base height up to the first alive primary branch was measured. This was followed by consecutive base height measurement of all primary branches of the tree and also base diameter of all those branches. The crowns were divided into six horizontal layers of approximately uniform depth and at each boundary, sample branches were selected and cut. All green shoots were detached from the sample branches and weighed. A sub-sample of shoots were collected and taken to laboratory for further measurements, whereby diameter and length of sub-sample shoots was measured and all needles clipped. We measured the needles length using a caliper and the base dimensions using microscope fitted with micrometers. Leaf area of a single needle was estimated by adding surface areas of all the four faces and then added up for the whole sub-sample. The ratio of leaf area to sub-sample shoot weight was used to estimate leaf area of sample trees. Allometric equation was formed using sample tree's dbh against leaf area as shown in Figure 2, which was then used to estimate plot leaf area using the measured stem's dbh in each plot. Finally, the LAI of *C. japonica* was calculated in the same way as for other species.

Laser data were collected in 2005 and ground survey carried out in 2010. The adjustment of time gaps between laser measurements and ground survey relationship was performed with forest inventory data carried out in 2000 containing stand biomass and age. Parameters were fitted to get theoretical growth equations as described by Sweda et al. (1984) and Draper and Smith (1998).

Deriving a function for relationship between LAI and vegetation profile area

We explored Beer-Lambert's law and dimensional analysis to find a reasonable function for the relationships of ground-based and laser estimated LAI. According to Beer-Lamberts Law, light transmittance decreases exponentially when it passes through a media. The application of this law in forestry was originally proposed by Monsi and Saeki (1953) and reviewed by Tadaki (2005). It has been widely applied in indirect estimation of LAI using optical light sensors. However, studies of Breda (2003) and Moser et al. (2007), indicate that these indirect methods are limited to small areas, they underestimate LAI in larger areas and fail to function properly in dense multilayer canopies. Therefore, mensurational application and laser technology has been suggested in this paper to complement Beer-Lambert's law in landscape estimation of LAI. In forest environment, the amount of leaf area is proportional to

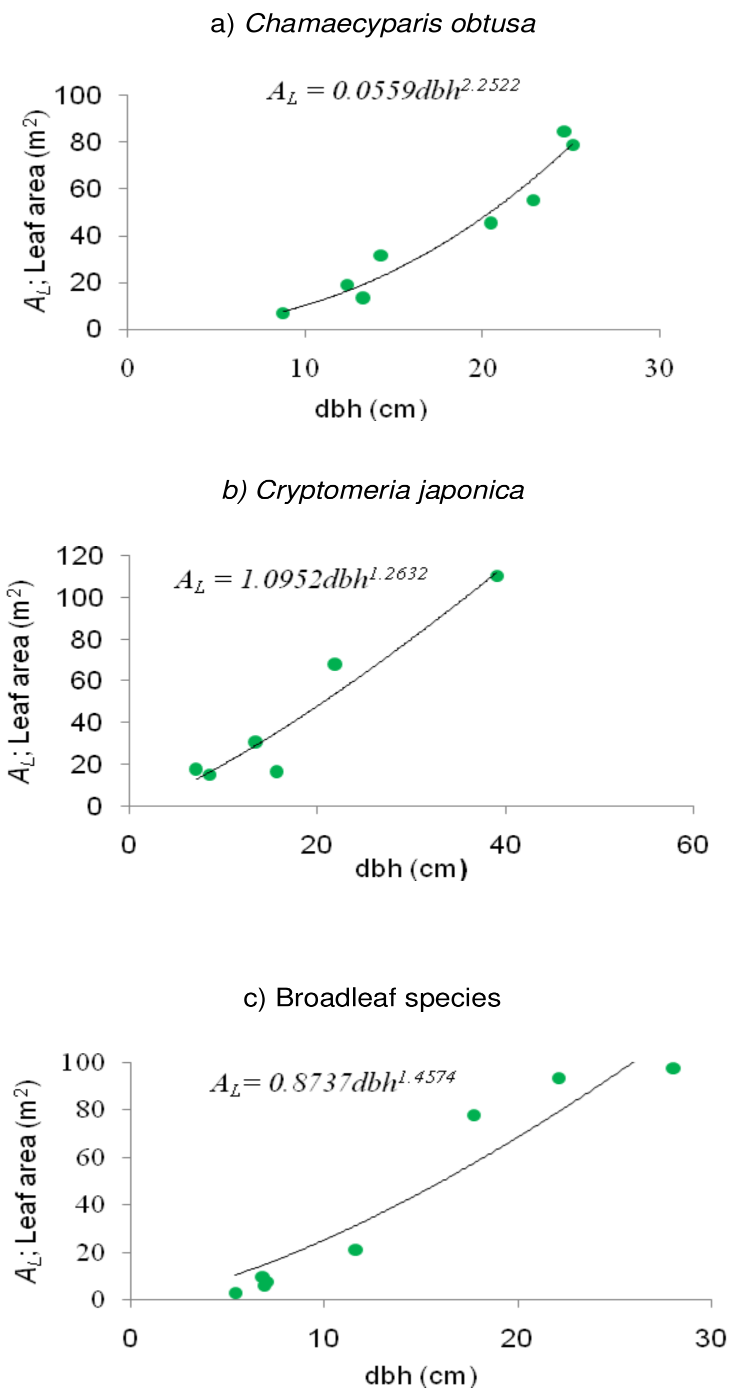

Figure 2. Leaf area allometric equations for a) *Chamaecyparis obtusa,* b) *Cryptomeria japonica* and c) broadleaf species.

crown depth (d_c) and consequently proportional to forest height (Mencuccini and Grace, 1994; Clark et al., 2008). Furthermore, mean vegetation height (h) is approximately equal to mean S (Equation 2):

$$\overline{h} = \int_a^b h(x)dx / b - a = \overline{S} \quad (2)$$

where x is distance along flight course, while a and b are values along x. The LAI increases with d_c and thus with S, but remain constant at d_c climax, according to Beer-Lambert's law. Furthermore, LAI increases in proportion with the growth allowance bounded by the maximum crown depth set by Beer Lambert's law (Figure 3). This assumes that LAI has an upper limit, which is important to calculate. Theoretically, the rate of LAI increases at any given S proportionally to the difference between the upper limit,

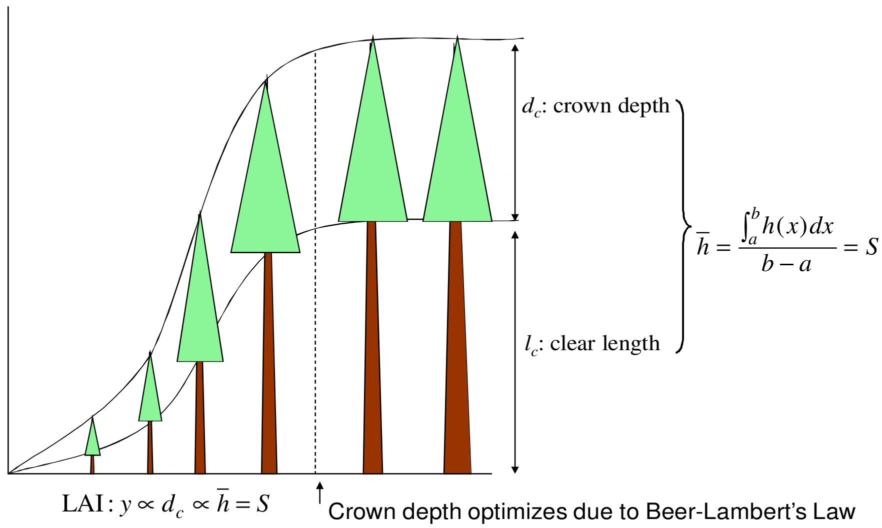

Figure 3. Generalized illustration between LAI and vegetation/forest profile area.

say *L,* and the amount of LAI, say *y*, achieved by that situation, as shown in Equations 3 and 4.

$$dy/dS = k(L - y) \tag{3}$$

where, *k* is rate of intrinsic increase of LAI. Integrating Equation (3) gives

$$LAI = L(1 - e^{-kS}) \tag{4}$$

Figure 3 illustrates generalized theoretical illustration of derived function. The goodness of the model was evaluated by root mean square error (RMSE) and bias (Helskanen, 2006) which was calculated as shown in Equations 5 and 6, respectively;

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \tag{5}$$

$$Bias = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \tag{6}$$

Where y_i is the observed, $\hat{y}_i$ is the estimate of leaf area and *n* is the number of the observations.

RESULTS AND DISCUSSION

Using Equation (4), parameters were fitted using nonlinear least square method with JMP ver. 9 Statistical software through iterative process until selected values converge. A model was plotted with LAI of all plots on the y-axis and *S* on the x-axis (Figure 4). The model clearly shows that theoretically the upper limit of LAI in the study area is achieved around a mean value of 10.7, when all species are combined beyond which no increase of LAI is expected. However this value should be taken as preliminary, since the sample size was rather small. However, as there is no other existing research in the study area, this value can be used as a point of reference in short term management programmes or as an important reference for future studies. Actually, the significant log-transformed correlation of 0.6 (p = 0.017) indicated that derived function is equally good for estimation of LAI.

The legitimacy of derived function (Equation 4) was illustrated by plotting estimated LAI against real LAI for all the sample plots as shown in Figure 5. The solid diagonal trend line represents regression constrained to pass through the origin, while the broken trend line is the best fit regression without any constraints. The degree of dispersion of relationship between real and laser estimated LAI is less than expected value (1.0) - solid line at Figure 5. The real and laser estimated LAI are significantly correlated (r = 0.6 and p = 0.014). The underestimation of the actual LAI is limited to a lower boundary and overestimation to the upper one. This could be due to random variation resulting from the choice of sample plots or to the methods used in ground truthing.

However, the bias seems to be consistent, with underestimation and overestimation at lower and upper limits, respectively, with a possibility of an appropriate estimation. The RMSE and bias of 1.32 and 0.21 compares well with studies of Tang et al. (2012); Richardson et al. (2009) and Jensen et al. (2009) who used recent technologies in estimation of LAI in larger areas. Our results showed that ALA slightly overestimates LAI of real plot averages for about 0.2. This portrays the potential of ALA to estimate LAI over

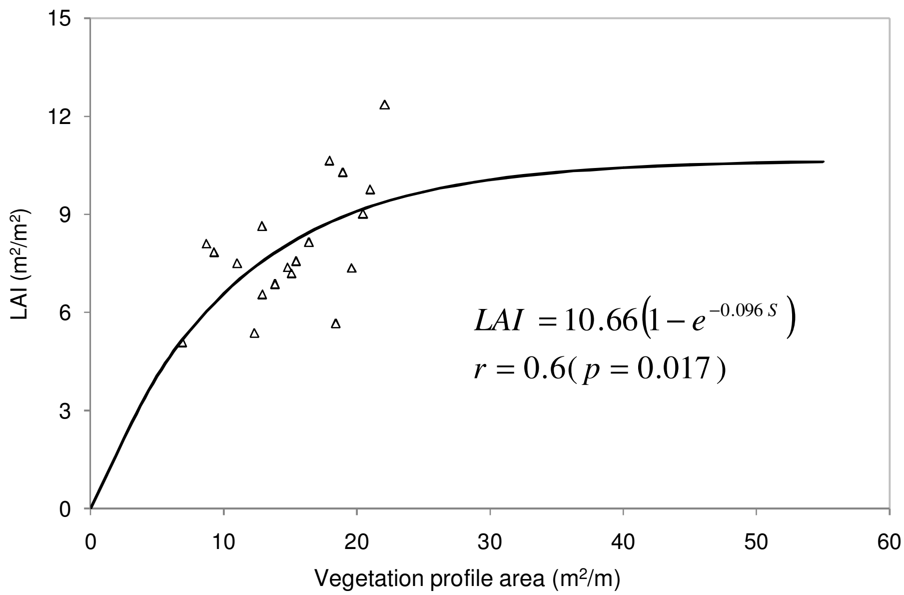

Figure 4. Relationship between LAI and vegetation profile area.

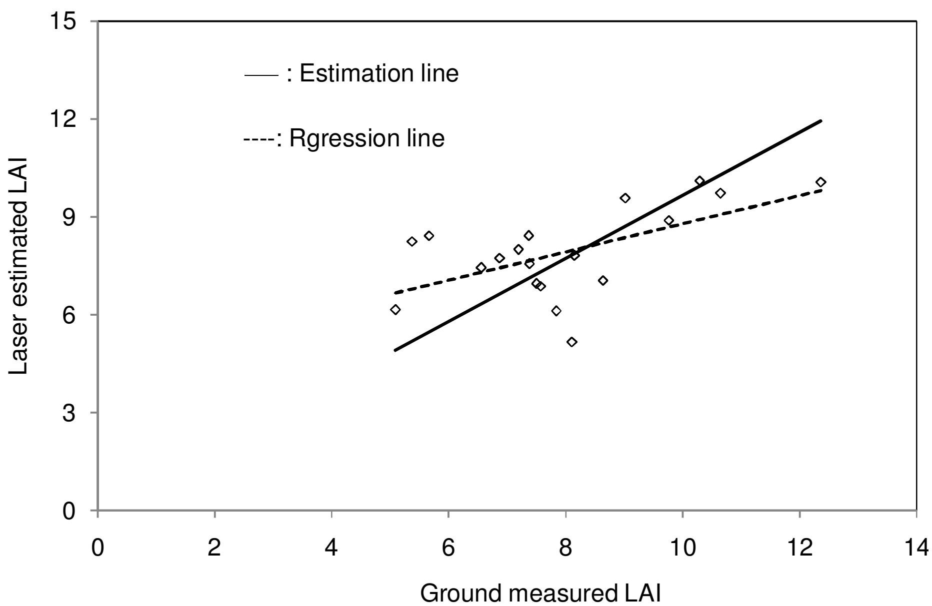

Figure 5. Comparison of ground measured LAI and laser estimates; (RMSE = 1.32 and bias = 0.21).

the extensive areas. Roberts et al. (2005) also reported overestimation of leaf area, although the study only involved estimating individual tree leaf area using laser metrics.

Using parameterized equations in Figure 4 and mean vegetation profile area of seven lasers transects, mean LAI was estimated at 8.3. This value compares well with other studies in the boreal and temperate forest as reviewed by Zheng and Moskal (2009). These estimations can also be regarded as reliable. A review of 89 research studies of LAI in Japanese forests, using direct and indirect ground methods in different regions, showed that LAI of conifer forests ranged from 5 to 10, and of broadleaves from 5 to 9 (Tadaki, 1977). The ground truth average LAI, which was used to calibrate laser derived vegetation profile, was 7.8 which, is actually within the range of existing literature. With the looming threat to mankind due to global warming currently underway, monitoring the climate change through modifications in extensive terrestrial vegetation has the paramount importance in choice of appropriate forest resource management to counter climate change. However, the minute changes are difficult to capture by ordinary conventional forest inventory methods on sample plot basis as described by Tadaki (1977); Breda (2003), since local environmental changes, may also affect dynamics of forest structure and composition. The results from such small scale monitoring could be rather ambiguous over extensive areas.

Results of this study have demonstrated that ALA is a reliable method for application in forest sector. It's therefore expected that transition from research to practical application of airborne laser technology in forestry at diverse scales will increase in near future if the forest planners and policy makers consider this technology in their operations. Since ALA records data in a linear method, amalgamation with multi-spectral digital imagery could promote this technology to a realistic alternative to traditional forest inventory methods. With the improvements of new generation laser sensors, which have the capacity to record multiple returns and higher pulse rates, the estimation accuracy of even more biophysical forestry characteristics could be improved.

Conclusions

In this research, an important function relating LAI and vegetation profile area was derived for extensive estimation which can be parameterized with data from different regions. Although the study only covered a small area, it has proved that ALA not only estimates the biomass in extensive areas with high precision, but also LAI. We recommend validation of these results in larger areas, covering different geographical regions.

ACKNOWLEDGEMENTS

This study was funded by Japan International Cooperation Agency (JICA) under international cooperation program of the government of Japan, whom we are highly indebted. The Director, KEFRI is highly acknowledged for granting the first author permission for further studies in Japan. We cannot forget our colleagues in Ehime University, Forest Resources Department, who assisted us in field data collection. Professor Ikuo Ninomiya, Dr. James Kimondo and two anonymous reviewers are highly acknowledged for going through the draft manuscripts and providing valuable comments.

REFERENCES

Arora VK, Boer GJ (2005). A parameterization of leaf phenology for the terrestrial ecosystem component of climate models. Glob. Change Biol. 11(1):39-59.

Breda NJJ (2003). Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J. Exp. Bot. 54(392):2403-2417.

Clark DB, Olivas PC, Oberbauer SF, Clark DA, Ryan MG (2008). First direct landscape-scale measurement of tropical rain forest Leaf Area Index, a key driver of global primary productivity Ecol. Lett. 11:163-172.

Draper NR, Smith H (1998). Applied Regression Analysis, A wiley series in probability and statistics, New York. P. 706.

Enquist BJ, Niklas KJ (2001). Invariant scaling relations across tree dominated communities. Nature 140:655-660.

Fassnacht KS, Gower ST, MacKenzie MD, Nordheim EV, Lillesand TM (1997). Estimating the leaf area index of North central Wisconsin forests using Landsat Thematic Mapper. Remote Sens. Environ. 61:229-245.

Fournier RA, Mailly D, Walter JN, Soudan K (2003). Indirect measurements of Forest canopy structure from *in situ* optical sensors; In Wulber MA, Franklin SE (Editors), Remote sensing of forest environments: concepts and case Studies, Kluwer Academic Publishers, Massachusetts, USA. pp. 77-113.

Gower ST, Norman JM (1991). Rapid estimation of leaf area index in conifer and broadleaf plantations. Ecology 72:1896-1900.

Gregoire TG, Valentine HT, Furnival GM (2005). Sampling methods to estimate foliage and other characteristics of individual trees. Ecology 76:1181-1194.

Hall FG, Peddle DR, LeDrew EF (1996). Remote sensing of biophysical variables in boreal forest stands of *Picea mariana*. Int. J. Remote Sens. 17:3077-3081.

Hasegawa K, Matsuyama H, Tsuzuki H, Sweda T (2006). The effect of bidirectional reflectance distribution function on the estimation of vegetation indices and leaf area index (LAI): A case study of the vegetation in succession stages after forest fire in Northwestern Canada. J. Remote Sens. Soc. Jpn. 26:186-201.

Helskanen J (2006). Estimating aboveground tree biomass and leaf area in a mountain birch forest using ASTER satellite data. Int. J. Remote Sens. 27:1135-1158.

Ioki K, Imanishi J, Sasaki T, Morimoto Y, Kitada K (2010). Estimating stand volume in broad-leaved forest using discrete-return LiDAR: plot-based approach. Landsc. Ecol. Eng. 6:29-36.

Jensen JRL, Humes KS, Vierling LA, Hudak AT (2009). Discrete return lidar-based prediction of leaf area index in two conifer forests. Remote Sens. Environ. 112:3947-3957.

Kang S, Running SW, Limb JH, Zhao M, Park CR, Loehman R (2003). A regional phenology model for detecting onset of greenness in temperate mixed forests, Korea: An application of MODIS leaf area index. Remote Sens. Environ. 86(2):232-242.

Kusakabe T, Tsuzuki H, Hughes G, Sweda T (2000). Extensive forest leaf area survey aiming at detection of vegetation change in subarctic-boreal zone. Polar Biosci. 133:133-146.

Lefsky MA, Cohen WB (2003). Selection of Remotely sensed data, in Wulber MA, Franklin SE (Editors), Remote sensing of forest environments: Concepts and case Studies, Kluwer Academic Publishers, Massachusetts, USA. pp. 13-46.

Lefsky MA, Cohen WB, Spies TA (2001). An evaluation of alternate remote sensing products for forest inventory, monitoring and mapping of douglas-fir forests in western Oregon. Can. J. For. Res. 31:78-87.

Mencuccini M, Grace J (1994). Climate influences the leaf area/sapwood area ratio in Scots pine. Tree Physiol. 15: 1-10.

Monsi M, Saeki T (1953). U¨ ber den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung f€ur die Stoffproduktion. Jpn. J. Bot. 14:22-52. English translation, On the factor of light in plant communities and its importance for matter production, published in Ann. Bot. (2005) 95:549-567.

Moser G, Hertel D, Leuschner C (2007). Altitudinal Change in LAI and Stand Leaf Biomass in Tropical Montane Forests: A transects study in Ecuador and a Pan-Tropical Meta-Analysis. Ecosystems 198:229-242.

Nelson RF, Parker G, Hom M (2003). A portable airborne laser system for forest inventory, Photogramm. Eng. Remote Sens. 69(3):267-273

Nelson, R, Short A, Valentine M (2004). Measuring biomass and carbon in Delaware using airborne profiling LIDAR, Scand. J. For. Res. 19:500-511.

Pierce LL, Running SW (1988). Rapid estimation of coniferous forest leaf area index using portable integrating radiometer. Ecology 69:1762-1767.

Richardson JJ, Moskal MM, Kim S (2009). Modeling approaches to estimate effective leaf area index from aerial discrete-return LIDAR, Agric. Forest. Meteorol. 149:1152-1160.

Roberts SD, Dean T J, Evans DL, McCombs JW, Harrington RL, Glass PA (2005). Estimating individual tree leaf area in loblolly pine plantations using LiDAR-derived measurements of height and crown dimensions. For. Ecol. Manage. 213:54-70.

Shinozaki K, Yoda K, Hozumi K, Kira T (1964). A quantitative analysis of plant form: The pipe model theory. II. Further evidence of the theory and its application in forest ecology. Jpn. J. Ecol. 14:133-139.

Sitch S, Huntingford C, Gedney N, Levy PE, Lomas M, Piao SL, Betts R, Ciais P, Cox P, Friedlingstein P, Jones CD, Prentice IC, Woodward FI (2008). Evaluation of the terrestrial carbon cycle, future plant geography, and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). Glob Change Biol. 14(9):2015-2039.

Spanner MA, Johnson L, Miller J, McCreight R, Freemantle J, Runyon J, Gong P (1994). Remote sensing of seasonal leaf area index across Oregon transects. Ecol. Appl. 4:258-271.

Stockli R, Rutishauser T, Dragoni D, O'Keefe J, Thornton PE, Jolly M, Lu L, Denning AS (2008). Remote sensing data assimilation for a prognostic phenology model. J. Geophys. Res. 113(G4):G04021.

Sweda T, Umemura T, Tanaka J (1984). Applicability of growth equations to the growth of trees in stem radius. Accuracy of projections. J. Jpn. For. Soc. 67:327-331.

Tadaki Y (1977). Leaf biomass, In Shidei T and Kira T (editors), Primary productivity of Japanese forests: Productivity of terrestrial communities, University of Tokyo Press, Tokyo, Japan. JIBP Synthesis 16:39-44.

Tadaki H (2005). Development of the Monsi-Saeki Theory on canopy structure and function. Ann. Bot. 95:483-494.

Tang H, Dubayah R, Swatantran R, Hofton M, Sheldon S, Clark D, Blair B (2012). Retrieval of vertical LAI profiles over tropical rain forests using waveform lidar at La Selva, Costa Rica. Remote Sens. Environ. 124:242-250.

Tsuzuki H, Nelson RF, Sweda T (2008). Estimating of timber stock of Ehime Prefecture Japan using airborne laser profiling. J. For. Plann. 13:259-265.

Turner DP, Acker SA, Means JE, Garman SL (2000). Assessing alternative allometric algorithms for estimating leaf area of Douglas-fir trees and stands. For. Ecol. Manage. 126:61-76.

Wulder MA, LeDrew EF, Franklin SE, Lavigne MB (1998). Aerial image texture information in the estimation of northern deciduous and mixed wood forest leaf area index (LAI). Remote Sens. Environ. 64:64-76.

Zheng G, Moskal LM (2009). Retrieving leaf area index (LAI) using remote sensing: theories, methods and sensors. Sensors 9:2719-2745.