Summary
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For effective management of natural forests as well as plantations, yield assessment is an important tool. Proper yield assessment undoubtedly forms the basis for monitoring forestry operations, measuring the impact of various silvicultural treatments and devising appropriate management strategies for such resources. Such systematic inventories will help evolve long term silvicultural systems required to guarantee the health and vitality of forests. Moreover, accurate growth and yield assessment of plantations are vital for forest managers, tree farmers, researchers and wood based industries alike, based on which appropriate decisions for investment and harvest can be made. Any error in enumeration of yield will affect the economics of any forest or plantation programme. Hence before adopting a method for yield assessment, cost effectiveness, minimal requirement of manpower and minimal subjectivity in interpretation need to be given due consideration.

It is in this context that the Image Analyser technology comes in handy which combines the ease of adaptation, speed and accuracy. This technology has been widely used in biological studies to measure pollen, leaf, seed and root characteristics. Numerical information on colour, intensity, distance, area, perimeter, shape and other characteristics can be obtained from digital images which are amenable to further analyses and interpretation. Image analyzer (IA) can be used to measure biometrics with possible frame calibration. In the case of trees, height and diameter are two dimensional characters which can be recorded in the IA from which volume can be estimated after applying species specific form factors.

This study focused on estimating the volume of wood and yield from a plantation based on digital image of the plantation by quantifying the variation in light reflection capacity of tree trunk, developing model for prediction of ground distance from the reflected light, optimization of method for estimation of crop diameter, optimization of plot area, establishment of relationship between height and diameter, quantification of location and clone specific form factor values and comparison of the different methods and instruments in estimation of volume. In short this study endeavored to standardize
timber yield assessment for Eucalypts using image analyzer and the stated objectives were to assess the variation in the reflection level of different clones and develop model for prediction of ground distance, to optimize the methods for basal area measurement using reflectance spectrum, to study the relationship between the height and basal area for different clones/locations, to estimate the variation in form factor for different clones/locations and to compare the different methods of volume measurements to find out the effectiveness of image analysis method.

Eucalyptus clonal plantations across five locations of Tamil Nadu were chosen for the study. In order to have uniformity in cultivation and management practices, the Eucalyptus plantations located at Arimalam, Kunnathur, Chittal, Siluvacherry and Warapur belonging to the administrative regions viz., Aranthangi, Villupuram, Thirukkovilur, Vridhachalam and Pudukottai respectively under Tamil Nadu Forest Plantation Corporation Limited (TAFCOR) were selected. Five commonly grown clones viz., Clone 3, Clone 7, Clone 10, Clone 271 and Clone 285 were considered in the study.

The methodology started with capturing digital image of the plantation after sunset using digital camera (Canon 450D) and flash light of fixed specifications. The terrestrial images of the plantations are subjected to image analysis. Image analyzer is software which can read the colour values in photographs. While taking the picture the breast height was marked in a tree facing the camera. A line is drawn at breast height level from left to right for making the profile reading. On command, the IA gives the Red, Green and Blue values for each pixel present in the line. These RGB values were subjected to noise removal at different threshold levels. The number of pixels present between the extreme threshold levels were counted and expressed as Pixel diameter (PD) of that particular tree.

For ground distance calibration, the average colour values of the reflected light per tree and its ground distance were subjected to regression analysis. The analysis was carried out with a sample of 240 trees and regression was developed for each clone and location. The pixel size varies based on the ground distance of the tree from the camera. Hence pixel size was calibrated by following an iterative method.
Later crop diameter was calculated in the following manner. For every specific tree, the pixel diameter and average Red or Green or Blue values were calculated. The ground distance was found out based on the average colour value. Based on the ground distance the pixel size was found out and multiplied with pixel diameter and actual diameter was arrived at. The same procedure was repeated for all the trees present in the frame and average value was taken to calculate the crop diameter. Based on the crop diameter, the basal area was calculated for the observed plot area. The height of the trees was predicted based on height diameter regression. The predicted height was multiplied with the basal area for arriving at the cylindrical volume and the same was multiplied with form factor for estimation of volume.

Subsequently, the variation in reflection capacity was studied in five different clones viz., Clone 3, Clone 7, Clone 10, Clone 271 and Clone 285 at five different locations viz., Arimalam, Kunnathur, Chittal, Siluvacherry and Warapur. Then ground distance prediction was done for the clones mentioned above. Later, the threshold levels and plot area were optimized for prediction of crop diameter. Similarly, the height and diameter relations for the above clones were studied for height prediction using a regression analysis. Before proceeding to compute the volume, Form Factor was calculated individually for each clone in all the study areas.

Finally, a comparative study was made regarding the accuracy of various dendrometers in estimation of volume. Height measurement was carried out with Haga Altimeter, Electronic Clinometer (Haglof) and Vertex Laser (Haglof). The actual height was measured after felling. The sample trees were assessed for diameter at breast height using tree callipers at two different directions and averaged. The plot was assessed for crop diameter using Wedge prism. The height of the trees was also predicted using the actual diameter measured using the callipers. The mean diameter for the plot was used to predict the height using the best fit regression equation. The measurements were compared with the results obtained from IA based on two digital picture frames for each sample plot. For this comparison, height and diameter measurements were made in three different locations viz., Arimalam, Chittal and Kunnathur for Clone 10, 285 and 3 respectively.
The salient findings of the study are given briefly as follows. There exists variation in the amount of reflected light with respect to location and clone. Clone 285 and Clone 271 exhibited higher reflectance and clone 10 recorded the least. The RGB values in the reflected light were found higher in Clone 271 and 285 compared to the other clones. With varying ground distance also, the clones studied exhibited similar behaviour as mentioned above. The Red, Green and Blue level in the reflected light at different ground distance showed a consistently decreasing trend as the ground distance increased. Blue level was consistently on the higher plane when compared to Red and Green levels up to 36 metres ground distance.

The regression equation developed for prediction of ground distance from the reflected light showed that the equation, \( y = a + bx/\ln x \) was common across different clones and colours especially for Chittal, Siluvacherry and Warapur. Arimalam and Kunnathur had two common equations viz., \( y = a + bx^3 \) and \( y = a + bx^{0.5} \) respectively followed by \( y = a + bx \ln x \). The \( r^2 \) value was high (above 0.75) for Siluvacherry and Warapur and low (above 0.60) for Arimalam, Kunnathur and Chittal. With respect to clones also no specific regression equation was common across the locations. Among the different colours, Red was found to have the better predictability with high \( r^2 \) values across different clones and locations.

Optimization of threshold levels for prediction of crop diameter showed that the diameter of the trees can be estimated with maximum accuracy at threshold level of 100 using Red spectrum with 1.13% Bias. Although the RMSE% was random at the location and clone level, it was observed to increase with increase in threshold level. Bias% was higher in Clone 271 and 285 when compared to Clone 7 and Clone 10 across different threshold levels.

Attempts were made at optimization of plot area and it was observed that the error in diameter measurement was the least at ground distance of 20-25 metres from the position of camera. It was observed that the error was on positive side when the trees are nearer and on negative side when the trees are farther from the camera in case of Red and Green spectra. Hence, circular sample plot with 30 meter radius eliminating trees present within 10 meter radial distance from the centre is found ideal. Within the
specified plot area the Bias Error increased consistently when ground distance increased. The polynomial equations developed between the ground distance and reflectance showed very high $r^2$ values which resulted in evolving highly dependable correction factors. The estimated diameter can be rectified based on the correction factors which can further reduce the error due to ground distance.

Height and diameter relation studies conducted for prediction of height brought out a wide range of equations for various clones/locations. However, the equations such as $y=a+b\ln x$, $y=a+b(lnx)^2$ and $y=a+b/x^{0.5}$ were recurring frequently across different locations/clones. Between clones and locations the $r^2$ values varied from 0.58 to 0.89 wherein the least values were recorded for Clone 285 at Kunnathur and Clone 3 at Warapur which showed $r^2$ values 0.58 and 0.59 respectively. Location and clone specific models resulted in increase in $r^2$ values up to 0.89 thereby showing improved accuracy.

The form factor studies conducted in five different locations yielded an average form factor value of 0.506. The variation in form factor was higher between different locations than between different clones. Irrespective of clones, average form factor was on higher side in Siluvacherry (0.544) and Warapur (0.525) compared to Arimalam (0.468). Similarly, irrespective of locations, Clone 271 (0.515) and 7 (0.512) recorded higher average form factor values when compared to Clone 285 (0.489). About 7.5% deviation from the average form factor value was noticed between locations, especially in case of Siluvacherry (+7.5%) and Arimalam (-7.5%). In case of Clones like Clone 271 (+1.8%) and Clone 285 (-3.4%) the deviation from the average was less.

Different diameter measurement methods namely Wedge prism method and IA method were compared with tape measurement. Although these two methods were not significantly different from the diameter measured using tape, Wedge prism showed high Bias values and relative RMSE % value of -7.5 and 14.5 respectively. The IA method of diameter measurement showed minimum error with only 1.5 and 3.8 % Bias and relative RMSE% values respectively when compared to diameter measured using tape thereby establishing higher dependability and accuracy.
Height measured using Altimeter, Clinometer, Vertex laser instrument and regression method were compared with actual height measured after felling. The height measurements obtained from all these methods were not varying significantly. However, the Bias % was high in Altimeter measurement (-4.23) followed by Clinometer measurement (1.74) compared to height predicted through height – diameter regression method (-1.17). The relative RMSE values also reflected the above trend. The Vertex laser measurement and regression method had minimum error with about 1% bias with about 4% relative RMSE. Hence the study revealed that height prediction using regression method is reliable in terms of accuracy and thus can be used in volume estimation.

Volume was found under-estimated while using diameter measured by wedge prism as revealed by the Bias values which ranged from -12.5 to -17.5% with relative RMSE value of about 30%. Among the different methods of volume estimation, the height measurement using Vertex laser and diameter measured using IA method was found to have the least error. At the same time, the study proved that the height measured using regression method of height prediction was as accurate as that measured employing Vertex laser instrument. Hence, it can be concluded that diameter estimated by IA method and height predicted using regression method can be used for obtaining reliable volume estimates. It has an added advantage of eliminating physical field measurements.