CHAPTER 3

Results

3.1 Hyperion reflectance spectra

Figure 3.1a and 3.1b show spectral signatures (April and October) of different vegetation covers of SWS. The wavelength regions in which the basic plant components have strong absorption features are indicated on this figure. Because of pigment absorptions, the visible region of plants spectra with full foliage (October) shows a maximum reflectance at approximately 550 nm (Green) and lower reflectance at the 450 nm (blue) and red (680 nm). Beyond visible region (wavelengths > 700 nm), the spectra of vegetation covers show a strong rise in reflectance. The region of maximum reflectance 700–1300 nm is called the near-infrared plateau (NIR-plateau). Reflectance spectra of April month show less prominent green peak and negligible red absorption.

Figure 3.2a and 3.2b shows average Hyperion reflectance spectra (October) for high density and low density quadrats of teak, bamboo vegetation covers of SWS. Reflectance spectra of different density quadrats showed high variation in NIR (700-1300 nm) region and Short Wave Infra Red (SWIR 1300-2500 nm) region. High density quadrats of teak and bamboo vegetation covers showed high amount of reflectance in NIR and SWIR region in reflectance spectra acquired from October image.

Variation in phenology was distinct in vegetation covers of SWS. Vegetation in SWS witnesses its full foliage just after the monsoon season (in October month). Leaf shedding in teak and bamboo species starts from the months of November-December. In the month of April teak and bamboo vegetation covers appear completely leaf less. FCC of the Hyperion image subsets (October and April month) shows clear change in vegetation condition due to availability/unavailability of water (**Figure 12 and 13 of Chapter 2). Figure 3.3** demonstrates spectral dynamics of the three distinct vegetation covers of SWS (teak, bamboo and mixed vegetation). It shows maximum, minimum and average reflectance spectra of these three vegetation covers. Phenology of the different vegetation covers were clearly depicted in Hyperion reflectance spectra acquired from the October image (post monsoon) and April image (pre monsoon). Reflectance spectra acquired for the two different seasons (October and April) showed distinct difference in shape. Difference is pronounced in the visible region. Variations are seen in Near Infrared (NIR) and Short wave Infrared (SWIR) regions as well. Spectra reflected the phenological condition of the vegetation. October spectra demonstrate lush green state and April spectra showed the deciduous/senescence state. Shape of reflectance spectra (especially in visible region) obtained from October image shows the greenness of vegetation. There is a considerable dip in the red region (660-690 nm). This dip disappears in April reflectance spectra. Greenness signal is weak in April. Reflectance spectra (April month) of mixed vegetation cover differed from that of teak and bamboo as these trees hold green foliage.

3.2 Structural and floristic dynamics of the study area

Structure and floristic composition was measured for 9 quadrats (30 x 30m) of mixed vegetation cover. These quadrats were divided into three classes (3 quadrats each) based on density of trees and acquired NDVI values (NDVI value 0.40 to 0.50 low density quadrats, 0.50 to 0.60 moderate density quadrats, 60 to >0.70 high density quadrats). Holdridge Complexity Index (HCI), Basal area (m^2 ha^{-1}), Shannon divesrsity index (H'), Number of species per quadrat (Species density) were calculated from these quadrats. **Table 3.1** show all measured attributes. Linear regression models between basal area and the two indices were prepared **(Figure 3.4a and 3.4b)**. Both linear regression models worked well with R^2 values of 0.83 and 0.90 respectively. Formula for calculation of Holdridge Complexity Index (HCI), and Shannon diversity index (H'), were given below.

$$\mathrm{HCI} = \frac{HGDS}{10000}$$

$$H' = -\sum p_i \ln p_i$$

Holdridge Complexity Index (HCI) from Holdridge (1967), where H is canopy height (m), G is basal area ($m^2\,ha^{-1}$), D is density of stem. To estimate floristic diversity the Shannon diversity index (H') (Magurran, 2004) were used. Where p_i is the proportion of individuals from the i^{th} species.

Average reflectance spectra (October) for the three mixed vegetation classes shown in **(Figure 3.5).** The most important wavebands showing variation in reflectance are NIR (700-1300 nm) bands followed by SWIR (130-2500 nm) and red region (600–700 nm) wavebands.

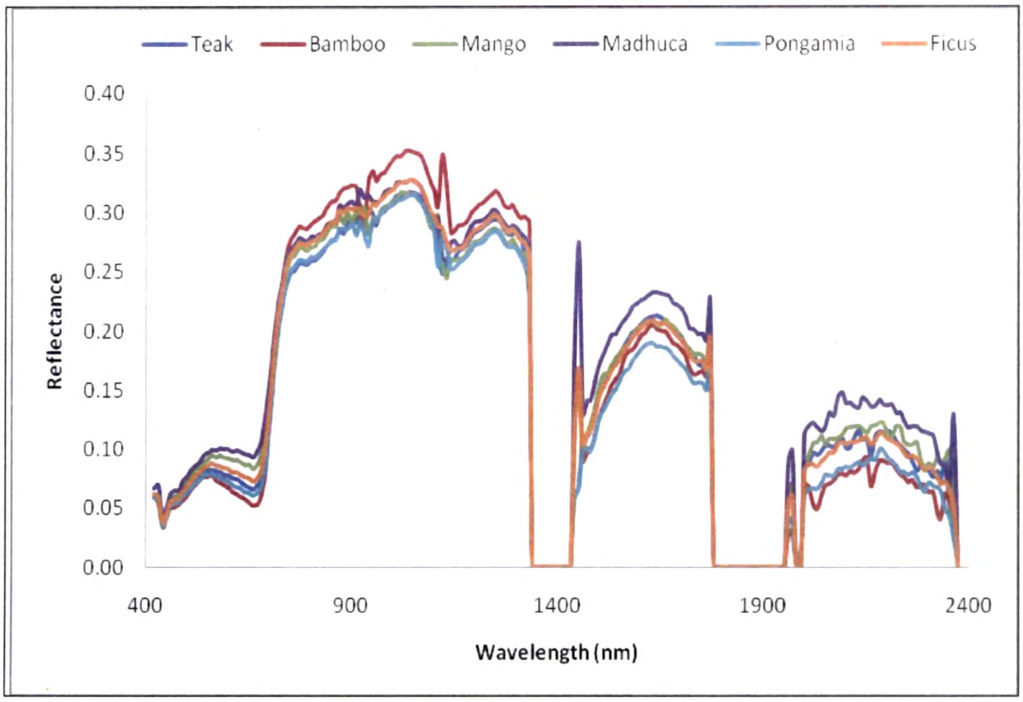


Figure 3.1a. Spectral signature of major vegetation covers of SWS (October)

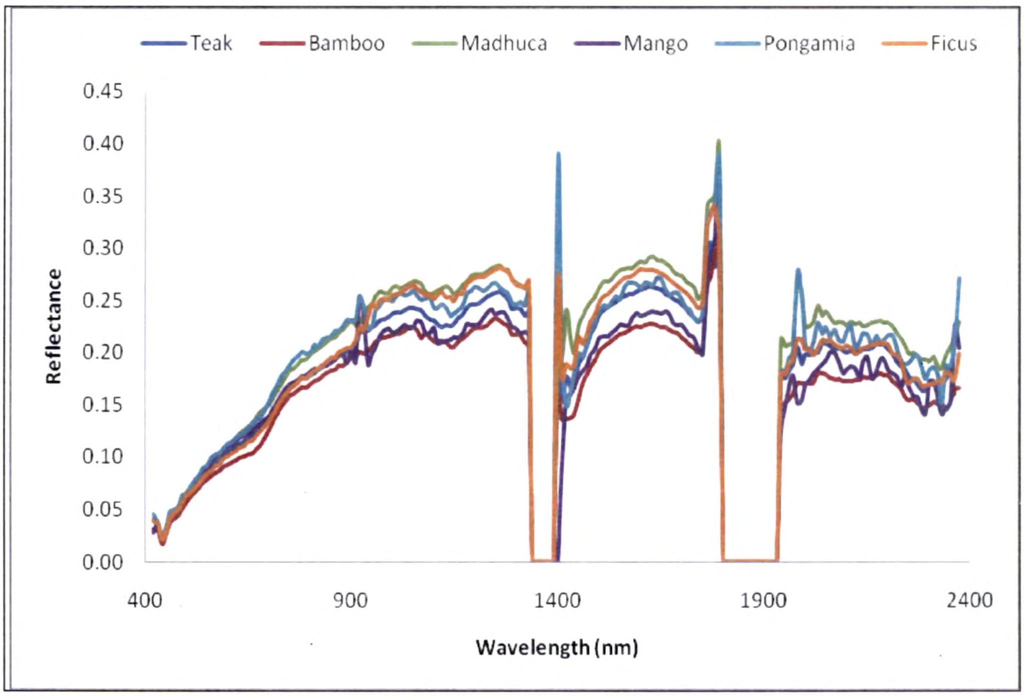


Figure 3.1b. Spectral signature of major vegetation covers of SWS (April)

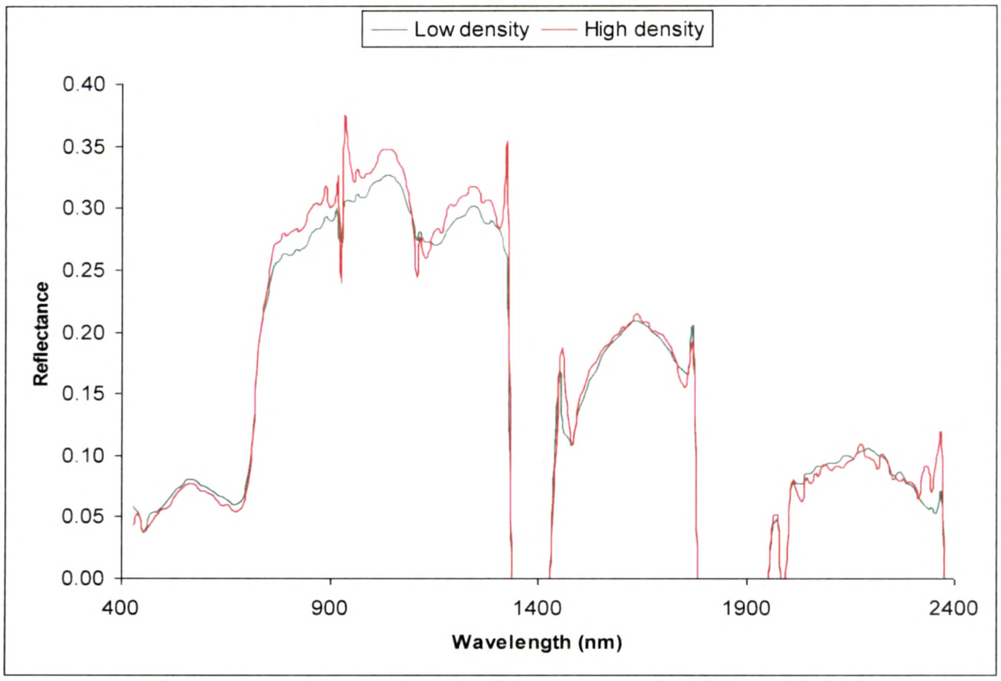


Figure 3.2a. Teak density Hyperion reflectance spectra

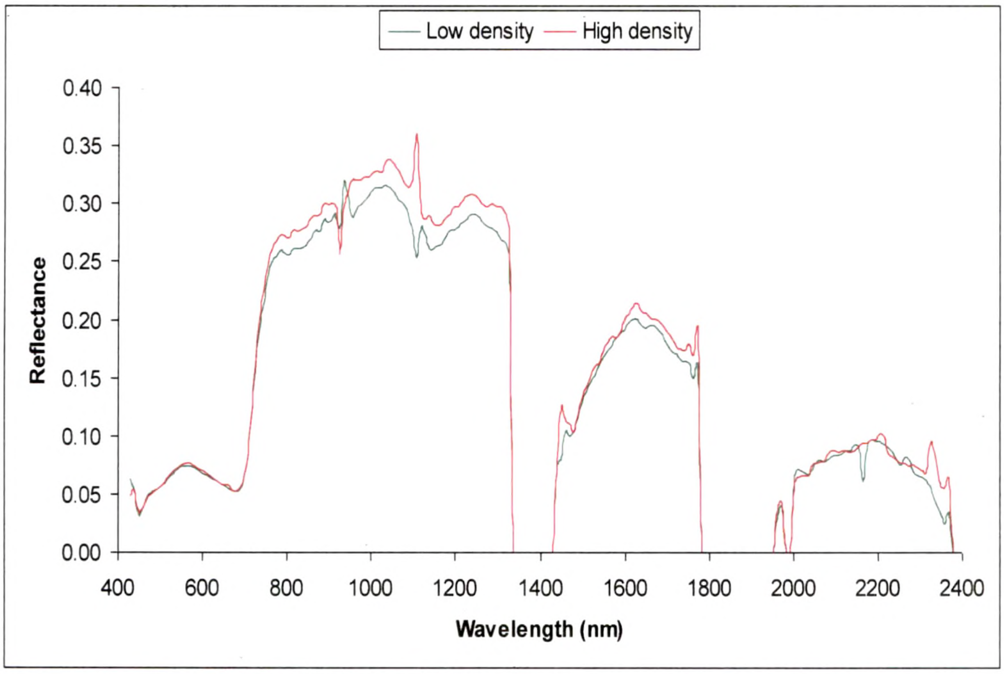


Figure 3.2b. Bamboo density Hyperion reflectance spectra

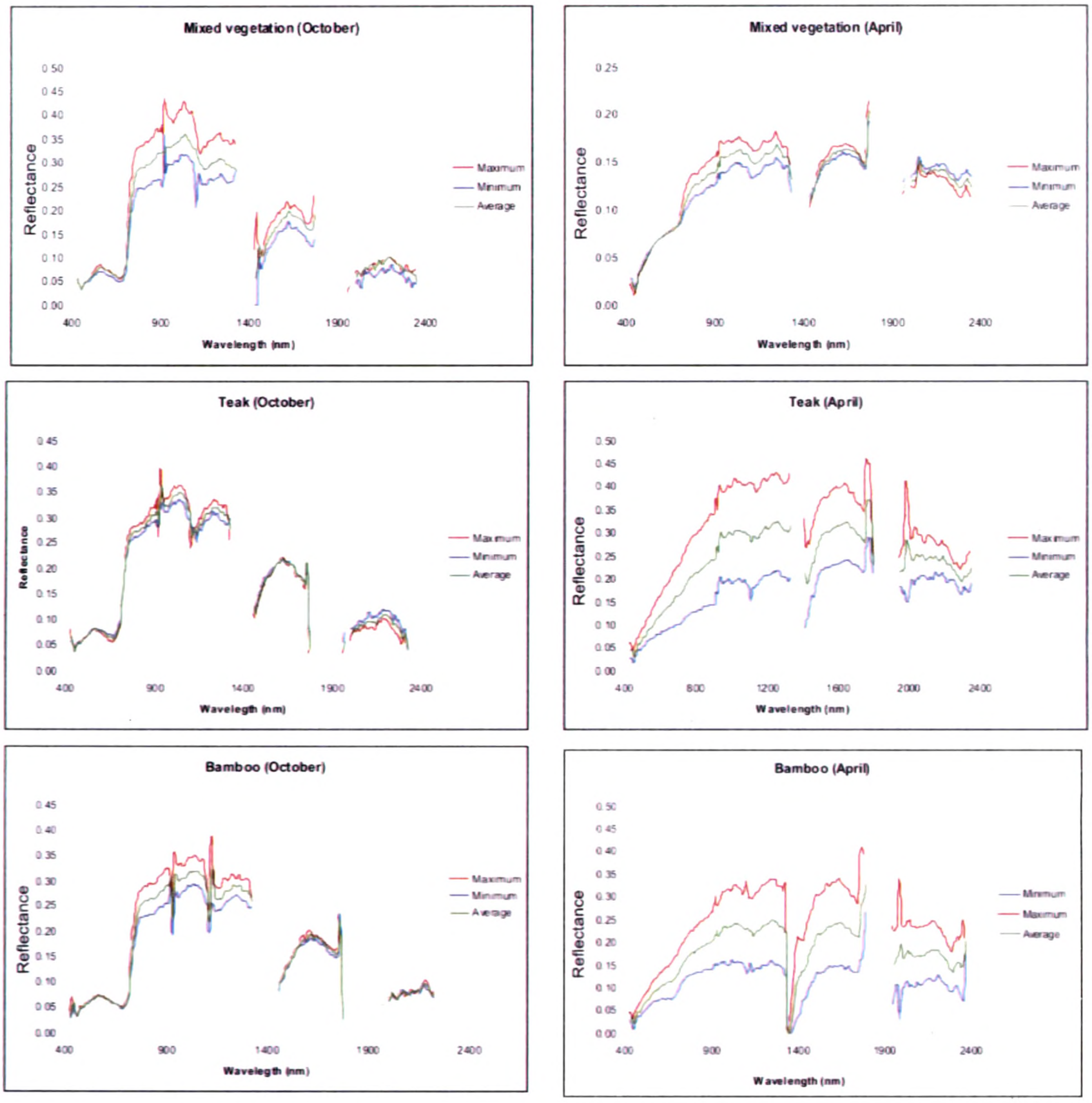


Figure 3.3. Hyperion reflectance spectra of three vegetation covers of SWS

Table 3.1. Structural and floristic dynamics of the mixed vegetation cover (Total number of quadrats n=9, 3 each of high ,moderate and low density)

Basal area m^2/ha (BA)			
Quadrat no.	High	Moderate	Low
1	47.43	32.47	15.76
2	44.06	32.90	20.67
3	41.94	31.50	14.39
Avg.	44.48±2.77	32.29±0.72	16.94±3.30
No of spp. (D)			
Quadrat no.	High	Moderate	Low
1	31.00	17.00	11.00
2	31.00	17.00	11.00
3	29.00	18.00	10.00
Avg.	30.33±1.15	17.33±0.58	10.67±0.58
No of trees. Species density (S)			
Quadrat no.	High	Moderate	Low
1	51.00	38.00	18.00
2	52.00	36.00	18.00
3	45.00	39.00	17.00
Avg.	49.33±3.79	37.67±1.53	17.67±0.58
Height m (H)			
Quadrat no.	High	Moderate	Low
1	21.03	18.90	18.10
2	21.20	17.80	18.90
3	22.10	19.50	18.20
Avg.	21.44±0.58	18.73±0.86	18.40±0.44
Holdridge complexity index (HCI)			
	High	Moderate	Low
1	178.05	39.64	7.79
2	170.00	36.84	8.16
3	142.37	43.12	6.29
Avg.	163.47±18.71	39.87±3.15	7.41±0.99
Shannon div. index(H')			
Quadrat no.	High	Moderate	Low
1	2.89	2.68	2.06
2	3.15	2.52	2.09
3	3.15	2.70	2.04
Avg.	3.06±0.15	2.63±0.10	2.06±0.03

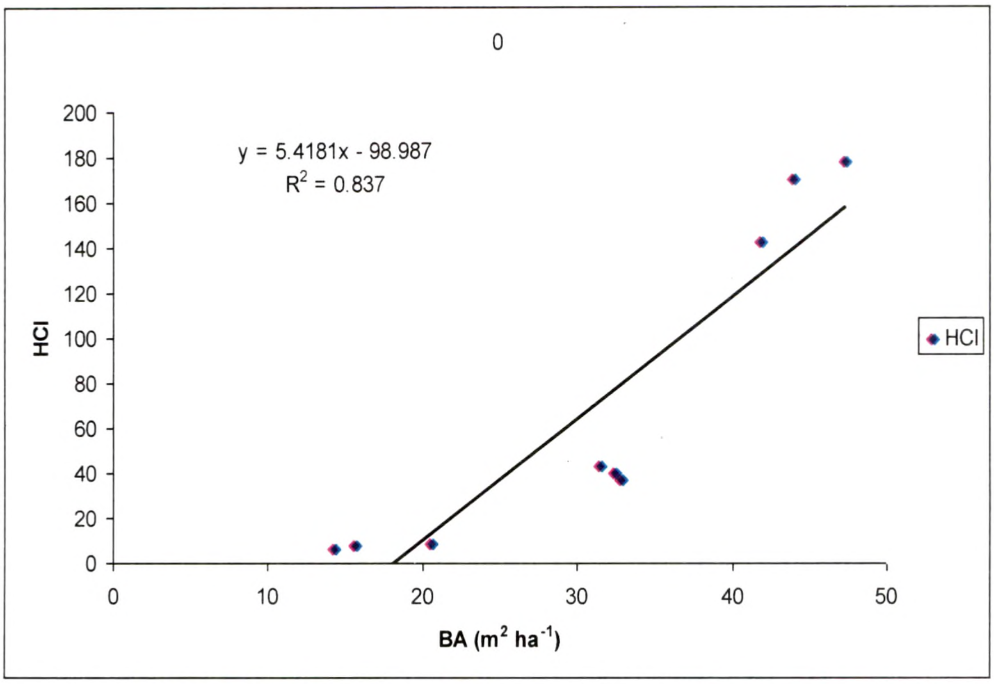


Figure 3.4a. Regression model prepared between BA and HCl

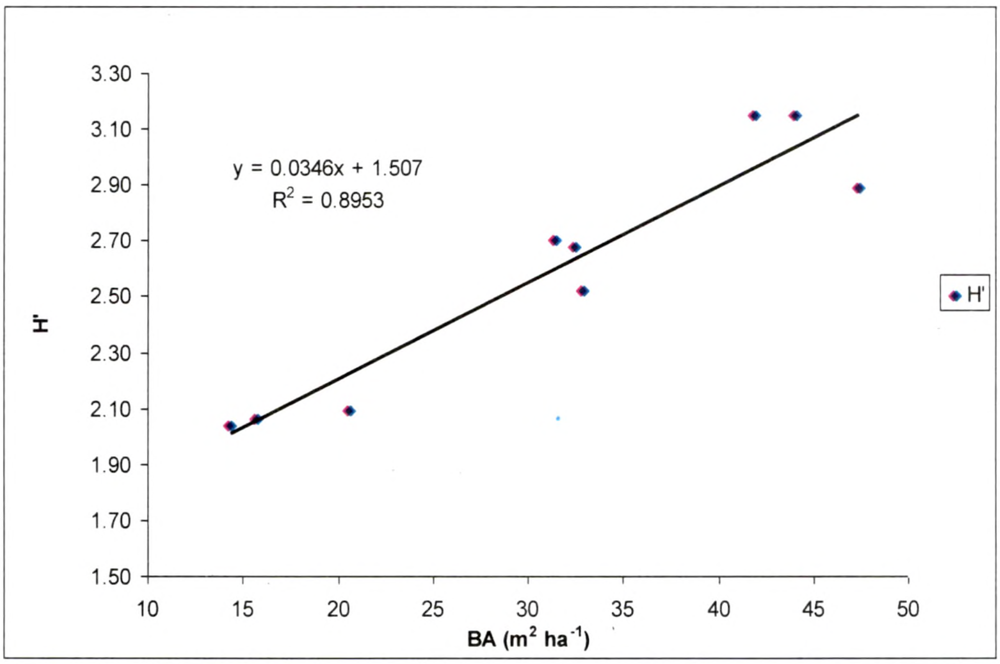


Figure 3.4b. Regression model prepared between BA and H'

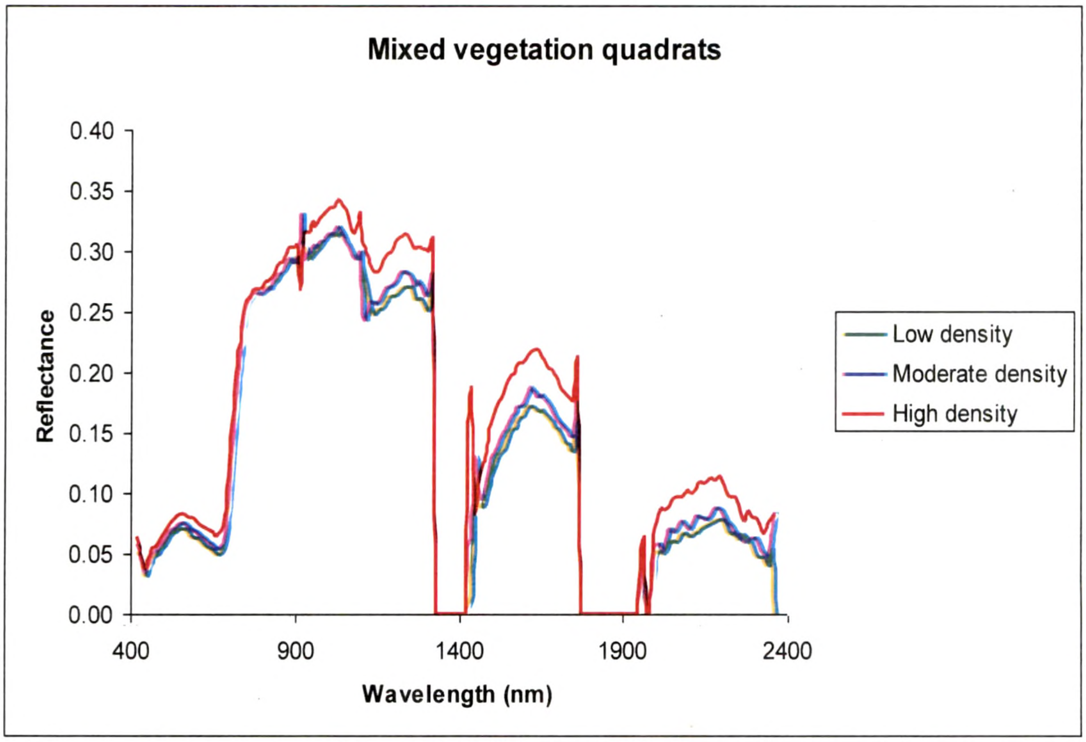


Figure 3.5. Average reflectance spectra (October) for the three mixed vegetation classes (high, moderate and low density)

3.3 Species level classification of Hyperion image subset (October)

Extensive field survey has identified eight distinct vegetation classes in the study area. Of these 8 classes, 6 classes are mainly represented by *Tectona grandis* (L.), *Dendrocalamus strictus* (Nees.), *Madhuca indica* (Gmel.), *Mangifera indica* (L.), *Ficus glomerata* (L.) and *Pongamia pinnata* (L.) respectively. Other two classes consist of mixed vegetation class and agriculture land. A total of 176 quadrats of 30x30 m size (corresponding with spatial resolution of Hyperion image, 30m) were marked across the study area **(Table 3.2).** 50 % of the marked quadrats were used as training site for supervised classification mechanisms. Normalized Difference Vegetation Index (NDVI) value of 0.40 was identified as threshold values for vegetation. Therefore, all the features in the image having <0.40 NDVI were masked during classification. **Figure 3.6a and 3.6b** show NDVI and mask image prepared for image classification of the study area.

Stepwise discriminant analysis (SDA) was performed for dimentionality reduction of Hyperion data to assess separability of eight tropical vegetation classes. SDA has ranked each band according to its ability to separate eight vegetation classes (lesser the Wilks' lambda, greater the separability between vegetation classes). Results are given in **Table 3.3**. SDA identified 22 optimal bands from 165 processed Hyperion bands. Of the 22 identified bands, five came from visible region, six from NIR region and eleven from SWIR region.

3.3.1 Hyperion image classification using 22 bands

These 22 bands were used for classification of Hyperion image (October) using Artificial Neural Network (ANN), Spectral Angle Mapper (SAM), Support Vector Machine (SVM) classifiers. **Figures 3.7** show classified images coming from ANN, SAM and SVM classifiers respectively. The image classified with ANN showed highest Over All Accuracy (OAA) of 81%, SVM showed 71% OAA and SAM gave the lowest OAA of 66%. **Tables 3.4a, 3.4b**

and 3.4c show confusion matrices prepared for the image classified with the three classifiers. Accuracy values were highest for vegetation classes with homogenous distribution such as *Tectona* and *Dendrocalamus.* All the three tested classifiers showed lesser accuracies (>70%) for vegetation with nonhomogenous distribution. Vegetation class of *Mangifera, Pongamia* and mixed vegetation showed lesser accuracy in ANN. SAM showed lesser accuracies for *Madhuca, Mangifera, Pongamia, Ficus* and Agriculture land classes. SVM showed lesser accuracies for agriculture land. SVM with 22 bands showed relatively lesser accuracy (as compared to the other two classifiers) for *Tectona* and *Dendrocalamus.* Among the three classifiers tested, ANN fared better for all vegetation classes while SAM showed lesser performance. SVM was moderate falling between ANN and SAM.

3.3.2 Hyperion image classification using all 165 bands

SAM, SVM classifiers were tested to check their efficiency in classifying Hyperion image using the entire Hyperion reflectance spectra (coming from 165 processed bands). **Figures 3.8a and 3.8b** are coming from these analyses. ANN could not classify the image with spectra coming from 165 bands. SAM showed an OAA of 62% and SVM showed 80% OAA for eight vegetation classes. **Tables 3.5a and 3.5b** show confusion matrices. SVM fared better. Classification accuracies of SVM using 165 bands are better than the ones coming from 22 bands. These values are very similar to the ones coming from ANN (with 22 bands).

Another important criterion considered for assessing the performance of classifier is, area classified as each vegetation class. **Figure 3.9** shows percentage area classified as each vegetation class in the three classifiers. All the three classifiers showed that about half of the pixels of image subset were classified as three major vegetation classes such as *Tectona, Dendrocalamus* and Mixed vegetation (about 19% of the pixels from the image were masked). In ANN about 49 % of pixels of image were classified as the three vegetation classes whereas it is 47%, 46% in SAM and SVM respectively. About 22 % of pixels were classified as two other vegetation classes (*Madhuca* and Agriculture land) by ANN whereas it is 24 % by SAM and SVM. Remaining vegetation classes did not contribute significantly in terms of classified pixels. Contribution of these classes (*Mangifera, Ficus* and *Pongamia)* is less then 5% of pixels in the three classifiers. Image classified with SVM classifier (for 165 available bands) showed similar pattern in percentages of pixels classified for each vegetation class as that of ANN.

Table 3.2. Total quadrats marked for each vegetation class in the study area for species level classification

Vegetation class	Number of quadrats marked
Tectona	40
Dendrocalamus	30
Madhuca	24
Mango	14
Pongamia	14
Ficus	14
Mixed vegetation	20
Agriculture land	20

Table 3.3. Bands selected with the help of Stepwise Discriminant Analysis

Wavelength (nm)	Wilks' lambda
1498	.018
1498,1578,	.014
1498,1578,2183	.011
1498,1578,2183,2275	.008
916,1498,1578,2183,2275	.007
916,1498,1578,1709,2183,2275	.005
559,916,1498,1578,1709,2183,2275	.004
509,916,1498,1578,1709,2183,2275,2264	.003
509,611,916,1498,1578,1709,2183,2275,2264	.003
509,611,916,953,1498,1578,1709,2183,2275,2264	.002
489,509,611,916,953,1498,1578,1709,2183,2275,2264	.002
489,509,611,916,953,1498,1578,1709,2183,2275,2235,2264	.001
489,509,611,916,953,1498,1578,1709,2183,2275,2235,2062,2264	.001
489,509,611,916,953,1003,1498,1578,1709,2183,2275,2235,2062,2264	.001
437,489,509,611,916,953,1003,1498,1578,1709,2183,2275,2235,2062,2264	.001
437,489,509,611,916,953,1003,1170,1498,1578,1709,2183,2275,2235,2062,2264	.000
437,489,509,611,916,953,1003,1170,1478,1498,1578,1709,2183,2275,2235,2062,2264	.000
437,489,509,611,916,953,973,1003,1170,1478,1498,1578,1709,2183,2275,2235,2062,2264	.000
437,489,509,611,631,916,953,973,1003,1170,1478,1498,1578,1709,2183,2275,2235,2062,2264	.000
437,489,509,611,631,916,953,973,1003,1170,1478,1498,1578,1709,2164,2183,2275,2235,2062,2264	.000
437,489,509,611,631,916,953,973,1003,1170,1478,1498,1578,1709,2153,2164,2183,2275,2235,2062,2264	.000
437,489,509,611,631,783,916,953,973,1003,1170,1478,1498,1578,1709,2062,2153,2164,2183,2235,2264,2275	.000

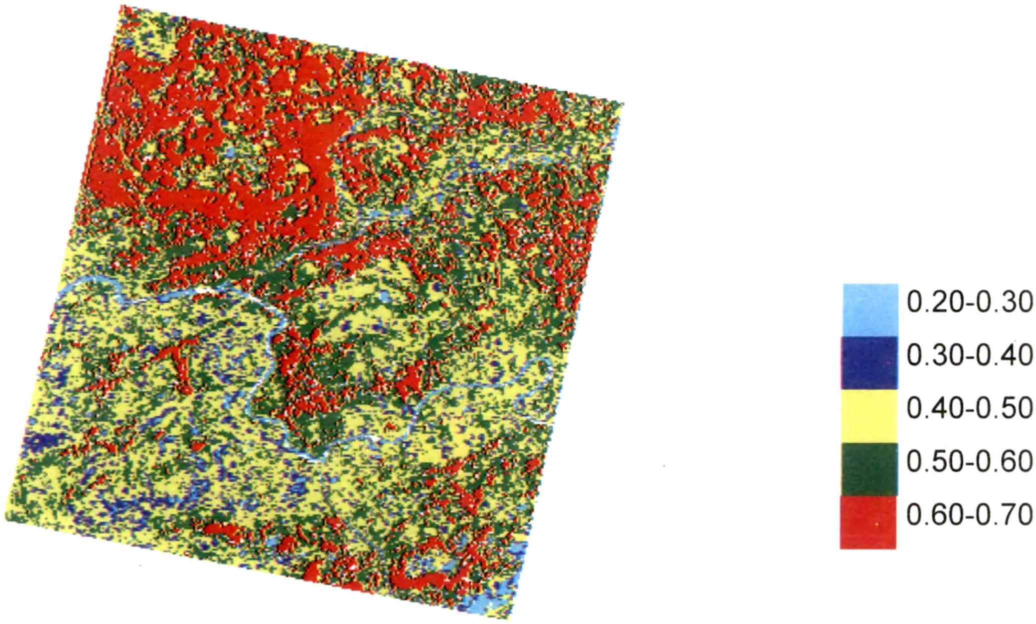


Figure 3.6a. NDVI (682 and 753nm) image subset (October)

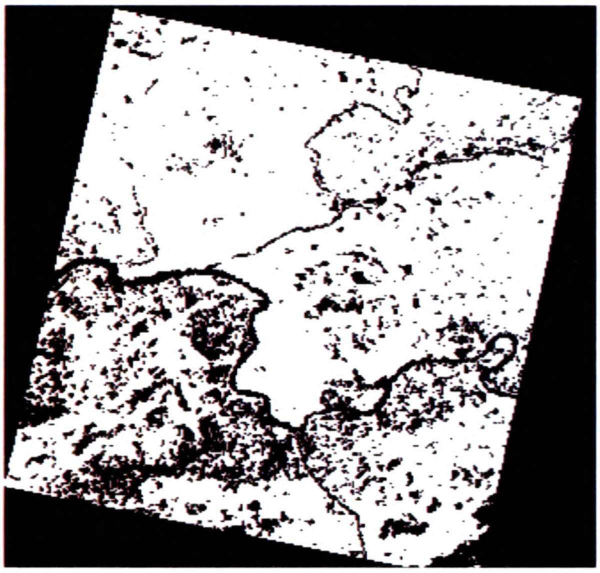


Figure 3.6b. NDVI mask image prepared for exclusion of non vegetation cover during classification (masked pixels marked in black colour)

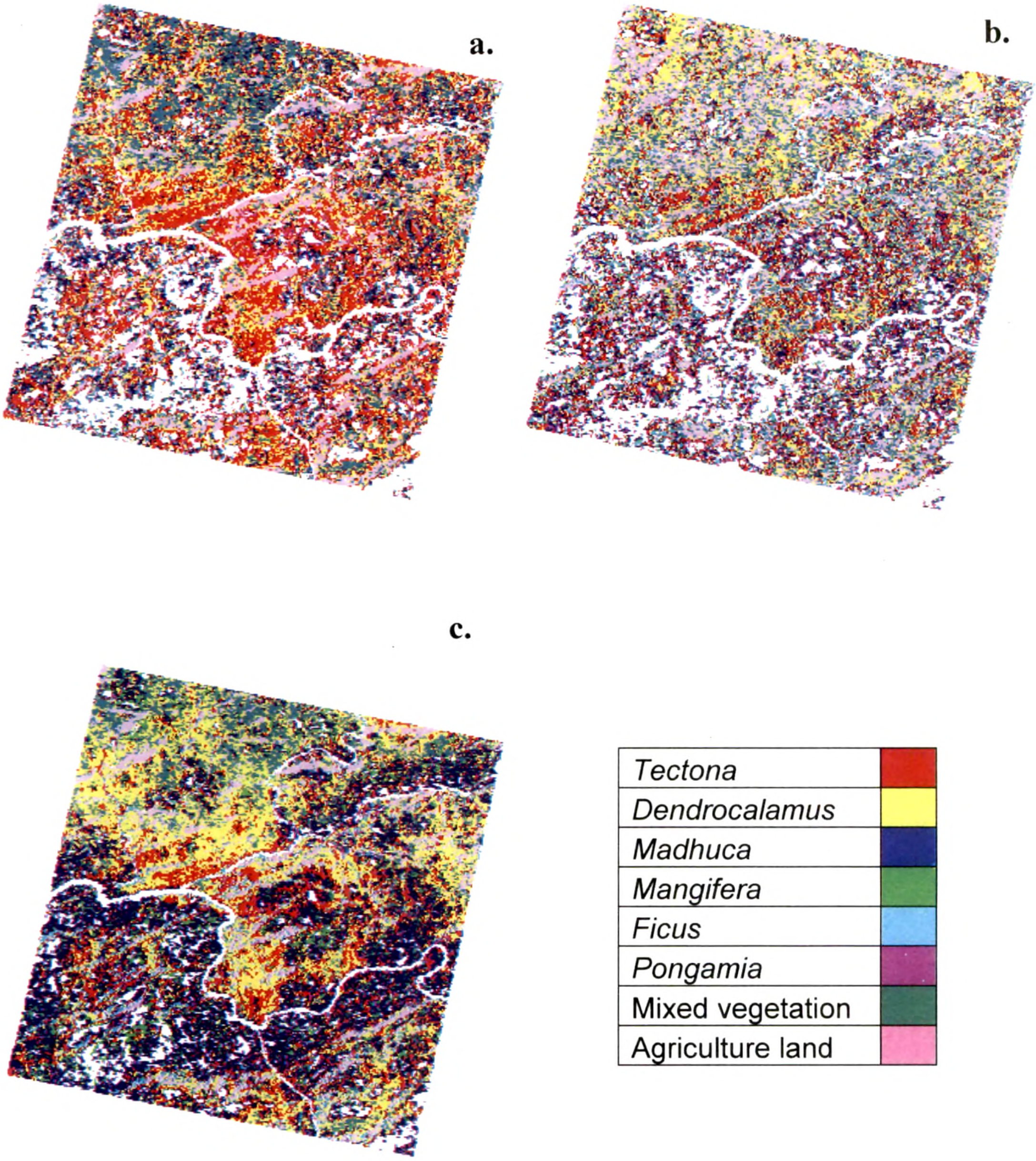


Figure 3.7. Images classified with (a) ANN, (b) SAM, and (c) SVM classifiers (22 isolated bands)

Table 3.4a. Confusion matrix obtained using ANN classifier with 22 selected bands

	Teak	Bamboo	Madhuca	Mango	Pongamia	Ficus	Mixed vegetation	Agriculture Land	Total	% Accuracy
Teak	**18**	1	0	0	0	0	0	0	19	94.74
Bamboo	1	**13**	0	0	0	0	1	0	15	86.67
Madhuca	0	0	**10**	0	0	0	0	0	10	100.00
Mango	0	0	2	**5**	0	0	0	1	8	62.50
Pongamia	0	1	0	0	**4**	1	0	0	6	66.67
Ficus	0	0	0	0	0	**5**	0	0	5	100.00
Mixed vegetation	1	0	0	0	3	1	**9**	0	14	64.29
Agriculture Land	0	0	0	2	0	0	0	**9**	11	81.82
Total	20	15	12	7	7	7	10	10	88	
% Accuracy	90.00	86.67	83.33	71.43	57.14	71.43	90.00	90.00		

OAA= 80.52%, Kappa coefficient =0.75

Table 3.4b. Confusion matrix obtained using SAM classifier with 22 selected bands

	Teak	Bamboo	Madhuca	Mango	Pongamia	Ficus	Mixed vegetation	Agriculture Land	Total	% Accuracy
Teak	**15**	3	0	0	1	0	0	0	19	78.95
Bamboo	3	**11**	0	0	0	0	0	0	14	78.57
Madhuca	1	0	**8**	2	2	0	0	0	13	61.54
Mango	0	0	2	**3**	0	0	0	0	5	60.00
Pongamia	0	0	0	0	**2**	2	1	0	5	40.00
Ficus	0	1	0	0	1	**5**	1	0	8	62.50
Mixed vegetation	1	0	0	0	0	0	**8**	1	10	80.00
Agriculture Land	0	0	2	2	1	0	0	**9**	14	64.29
	20	15	12	7	7	7	10	10	88	
% Accuracy	75.00	73.33	66.67	42.86	28.57	71.43	80.00	90.00		

OAA= 65.98%, Kappa coefficient =0.60

Table 3.4c. Confusion matrix obtained using SVM classifier with 22 selected bands

	Teak	Bamboo	Madhuca	Mango	Pongamia	Ficus	Mixed vegetation	Agriculture Land	Total	% Accuracy
Teak	16	4	3	0	0	0	0	0	23	69.57
Bamboo	4	11	0	0	0	0	1	0	16	68.75
Madhuca	0	0	9	0	0	0	0	0	9	100.00
Mango	0	0	0	3	0	0	0	1	4	75.00
Pongamia	0	0	0	0	4	0	0	0	4	100..00
Ficus	0	0	0	1	0	4	0	0	5	80.00
Mixed vegetation	0	0	0	1	3	0	9	0	13	69.53
Agriculture Land	0	0	0	2	0	3	0	9	14	64.29
	20	15	12	7	7	7	10	10	88	
% Accuracy	80.00	73.33	75.00	42.86	57.14	57.14	90.00	90.00		

OAA= 70.68%, Kappa coefficient =0.64

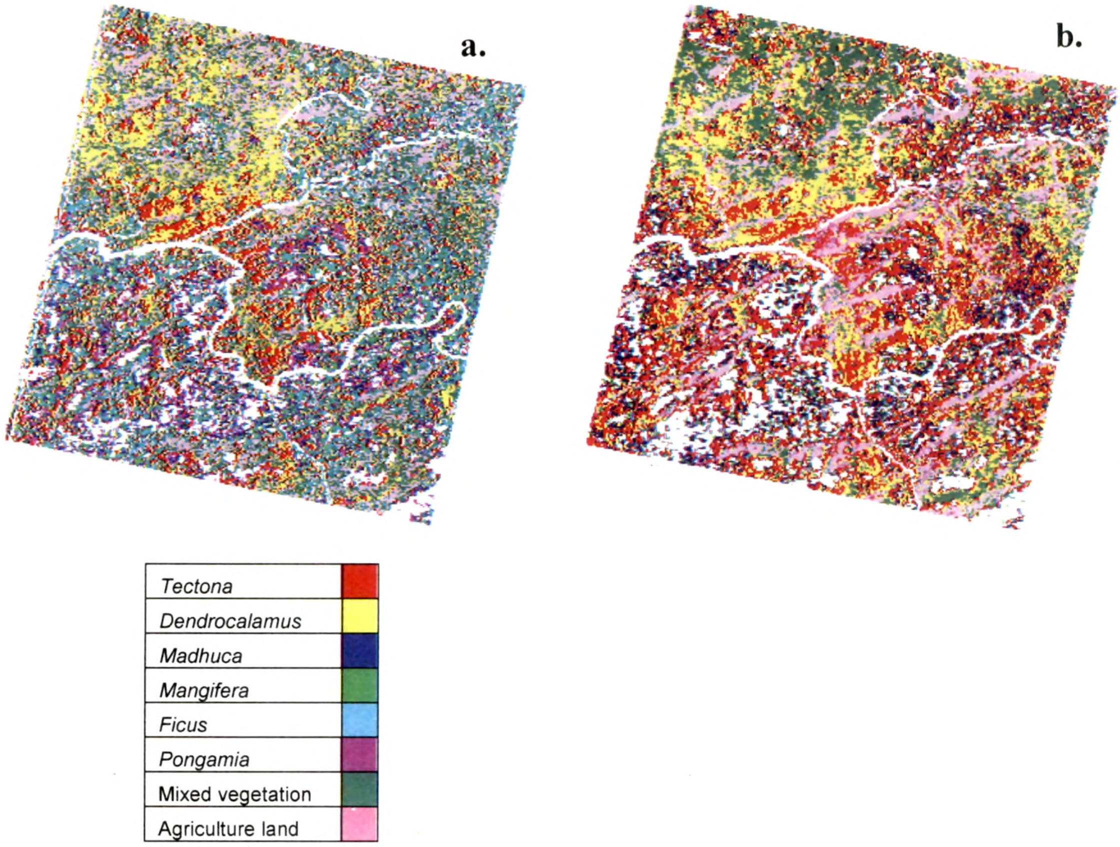


Figure 3.8. Images classified with (a) SAM and (b) SVM classifiers (all 165 bands)

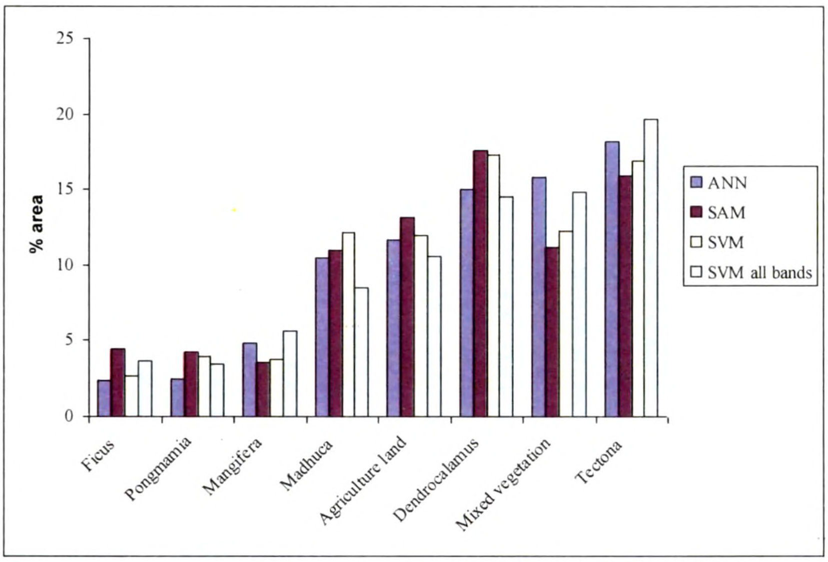


Figure 3.9. Percentage area occupied by 8 tropical vegetation classes in the image subset classified with different classifiers

Table 3.5a. Confusion matrix obtained using SAM classifier with all 165 bands

	Teak	Bamboo	Madhuca	Mango	Pongamia	Ficus	Mixed vegetation	Agriculture Land	Total	% Accuracy
Teak	15	3	0	0	1	0	0	0	19	78.95
Bamboo	3	11	0	0	0	0	0	0	14	78.57
Madhuca	1	0	8	2	2	0	0	0	13	61.54
Mango	0	0	2	3	0	0	0	0	5	60.00
Pongamia	0	0	0	0	2	4	1	0	7	28.57
Ficus	0	1	0	0	1	3	1	0	6	50.00
Mixed vegetation	1	0	0	0	0	0	8	1	10	80.00
Agriculture Land	0	0	2	2	1	0	0	9	14	64.29
	20	15	12	7	7	7	10	10	88	
% Accuracy	75.00	73.33	66.67	42.86	28.57	42.86	80.00	90.00		

OAA= 62.41%, Kappa coefficient =0.59

Table 3.5b. Confusion matrix obtained using SVM classifier with all 165 bands

	Teak	Bambo o	Madhuc a	Mang o	Pongami a	Ficus	Mixed vegetatio n	Agricultur e Land	Tota l	% Accurac y
Teak	17	2	0	0	0	0	0	0	19	89.47
Bamboo	2	12	0	0	0	0	1	0	15	80.00
Madhuca	0	0	10	1	0	0	0	0	11	90.91
Mango	0	0	2	5	0	0	0	0	7	71.43
Pongamia	0	1	0	0	5	1	0	0	7	71.43
Ficus	0	0	0	0	0	4	0	0	4	100.00
Mixed vegetation	1	0	0	0	2	2	9	0	14	64.29
Agriculture Land	0	0	0	1	0	0	0	10	11	90.91
	20	15	12	7	7	7	10	10	88	
% Accuracy	85.0 0	80.00	83.33	71.43	71.43	57.1 4	90.00	100.00		

OAA= 79.79%, Kappa coefficient =0.74

3.4 Results for biophysical and biochemical attributes measurements

3.4.1 Measured biophysical attributes for three distinct vegetation covers

Biophysical attributes such as LAI and canopy area were measured in October. Bole biomass was measured in April **(Table 3.6a and 3.6b)**. Measured LAI ranged from 2.38-6.63 for teak and 3.27-6.41 for bamboo quadrats. Canopy area ranged from 265-942 m^2 per quadrat for teak and 315-915 m^2 per quadrat for bamboo (each quadrat cover an area of 30 × 30 m). Canopy area ranged from 204 to 1211 m^2 per quadrat for mixed vegetation. Bole biomass ranged from 28.30-264.30 t ha^{-1} and 47.5-75.10 t ha^{-1} for teak and bamboo respectively. For mixed vegetation quadrats biomass ranged from 31.73 to 268.10 t ha^{-1} . Bole biomass values in the three covers showed wider range indicating differences in growth phase of trees across study area.

3.4.2 Measured biochemical attributes for teak, bamboo and mixed vegetation covers

Biochemical attributes were measured in the foliar samples collected in the month of October **(Table 3.7).** Chlorophyll content for quadrats laid ranged from 0.77 to 2.64 g m^{-2} for teak and 1.22 to 2.55 g m^{-2} for bamboo. Nitrogen content ranged from 1.77 to 5.95 g m^{-2} for teak and 0.56 to 2.32 g m^{-2} for bamboo. Lignin content ranged from 41.60 to 150.70 g m^{-2} and 27.13 to 143.59 g m^{-2} for teak and bamboo respectively. Cellulose content was relatively higher (66.70 to 241.10 g m^{-2} for teak and 37.23 to 192.95 g m^{-2} for bamboo). EWT ranged from 46.15 to 165.63 g m^{-2} and 24.00 to 114.73 g m^{-2} for teak and bamboo indicating higher water content in teak foliage. These three attributes were not estimated in mixed vegetation cover for not having a standardized protocol for leaf area estimation. However, method for estimation of LAI (used for Teak and Bamboo) were applied for mixed vegetation but it failed in giveing good results. Biochemical constitutes of stem (lignin and cellulose) were measured when vegetation was in deciduous condition (April). Lignin content in stem is higher for teak (0.40 to 10.40 Kg m^{-2}) in comparison to bamboo (0.49 to 2.55 Kg

m^{-2}). Cellulose content in stem ranged from 1.30 to 12.60 Kg m^{-2} for teak and 0.72 to 3.76 Kg m^{-2} and for bamboo.

3.5 PLS regression analysis of biophysical attributes

Reflectance spectra acquired from October image were used for the estimation of canopy biophysical attributes (LAI and canopy area). Reflectance spectra obtained from April image were used for the estimation of bole biomass.

3.5.1 PLS regression (Full reflectance spectra)

PLS regression demonstrated strong predictive relationships between full Hyperion spectral reflectance and measured biophysical attributes. R^2 values for PLS regression models and obtained standard error for calibration (SEC), standard error for cross validation (SECV) were shown in **Table 3.8a and 3.8b and Figure 3.10.** Biophysical attributes such as (bole biomass and canopy area) were estimated with maximum accuracy with PLS regression models were developed with full (165 bands) Hyperion reflectance spectra. R^2 values ranged from 0.55 to 0.86. Highest R^2 values were obtained for the estimation of bole biomass for teak and bamboo quadrats (R^2 0.86 for teak and 0.80 for bamboo). PLS regression models developed for estimation of canopy area gave high R^2 values for teak quadrats (R^2 0.86). Bamboo did not show similar values (R^2 0.55). PLS regression models for LAI were developed for the combined data set of teak and bamboo. This facilitated in having a wider range for LAI and larger data set for analysis. R^2 value was better (0.72) for LAI.

3.5.2 PLS regression results (Spectral subset)

PLS regression models of spectral subset showed R^2 values ranging from 0.23 to 0.87 **(Figure 3.11).** PLS regression model developed for LAI was with highest accuracy (R^2 = 0.87). These R^2 values are better than the one coming from full spectra. Spectral subset models gave high R^2 values for bole biomass (R^2 0.86 for teak and 0.80 for bamboo). PLS regression models developed for canopy area gave high R^2 values for teak quadrats (R^2 0.72). This spectral subset did not give significant R^2 values for canopy area of bamboo (R^2 0.26). **Table 3.8a and 3.8b** shows obtained range of SEC and SECV values for biophysical attributes.

3.5.3 Cross validation of developed models

As an additional measure, an attempt has been made to estimate bole biomass and canopy area of mixed vegetation cover using PLS regression model developed with teak quadrats. Cross validation of PLS model will check the generalization capacity of that model. Cross validation procedure for bole biomass resulted in R^2 values of 0.83 for mixed vegetation. Cross validation procedure for canopy area resulted in R^2 values of 0.67 for mixed vegetation. **Table 3.9** shows SECV values for cross validation.

3.6 PLS regression analysis of biochemical attributes

Reflectance spectra acquired from October image were utilized for estimating biochemical attributes (chlorophyll, nitrogen, lignin, cellulose and EWT) at canopy level. Reflectance spectra of April image were tested for estimating major biochemical constitutes of stem (lignin and cellulose).

3.6.1 PLS regression analysis (Full reflectance spectra):

R^2 values obtained standard error for calibration (SEC) and standard error for cross validation (SECV) were shown in **Table 3.10a and 3.10b** and **Figure 3.12**. R^2 values of biochemical attributes coming from PLS regression models of full spectra were between 0.52-0.80. A strong predictive relationship between full Hyperion reflectance spectra and chlorophyll concentration was found (R^2 0.78 for teak and 0.80 for bamboo). High R^2 values were obtained for canopy lignin of teak and bamboo quadrats (R^2 0.70 for teak and 0.68 for bamboo). Canopy cellulose estimation through PLS regression models showed slightly lesser R^2 values (R^2 0.64

for teak and 0.67 for bamboo). EWT resulted in R^2 values of 0.70 for teak and 0.67 for bamboo. PLS regressions developed for teak and bamboo demonstrated reasonable predictive relationships between spectral reflectance and nitrogen concentration (R^2 values ranging from 0.63 to 0.67 for full Hyperion spectra). Lignin and cellulose contents of stem were well represented in PLS regression models developed for teak quadrats (lignin, R^2 0.74 and cellulose, R^2 0.79). Similar analysis for the clumps of bamboo gave poor results (lignin, R^2 0.52 and cellulose, R^2 0.53).

3.6.2 PLS regression (Spectral subset)

Table 3.10a and 3.10b and Figure 3.13 show R^2 values for subset obtained standard error for calibration (SEC), and standard error for cross validation (SECV). PLS regression models developed with the help of different spectral subsets worked well for most of the measured biochemical attributes (R^2 values ranged from 0.50 to 0.90). PLS regression model developed with spectral subset gave highest R^2 values for the estimation of chlorophyll in teak and bamboo quadrats (R^2 0.90 for teak and 0.81 for bamboo). PLS regression model developed with the help of spectral subset for estimation of stem lignin and stem cellulose also gave higher R^2 values (Stem lignin, R^2 0.80 for teak and 0.78 for bamboo and stem cellulose, R^2 0.75 for teak and 0.65 for bamboo). Other biochemical attributes such as nitrogen (R^2 0.70 for teak and 0.63 for bamboo), canopy lignin (R^2 0.74 for teak and 0.67 for bamboo) and canopy cellulose (R^2 0.72 for teak and 0.72 for bamboo) were also estimated with high accuracy when PLS regression model was developed with spectral subset. R^2 values obtained from subset were higher than R^2 values obtained by PLS regression models developed with full Hyperion reflectance spectra. PLS regression analysis developed with different spectral subsets of SWIR region achieved better R^2 values for EWT estimation in teak (R^2 =0.71). EWT estimation for bamboo did not give acceptable R^2 (0.50) with the same spectral subset.

Table 3.6a. Biophysical attributes for teak and bamboo

Biophysical attributes		Teak (n=35)			Bamboo (n=35)		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
Bole biomass	t ha^{-1}	28.30	264.30	126.31±80.09	47.50	75.10	60.771±7.71
Canopy area	m^2 0.1ha^{-1}	265.00	942.00	567.96±170.28	315.00	915.00	518.91±131.65
LAI*		2.38	6.63	4.14±1.35	3.27	6.41	4.54±1.40

***Results for LAI are coming from combined dataset of teak and bamboo.**

Table 3.6b. Biophysical attributes for mixed vegetation covers

Biophysical attributes	Mixed vegetation (n=30)		
	Minimum	Maximum	Mean
Bole biomass	31.73	268.10	141.71±7.71
Canopy area	204.00	1211.00	707.50±201.35

Table 3.7. Biochemical attributes for teak and bamboo

Biochemical attributes		Teak (n=35)			Bamboo (n=35)		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
Chlorophyll	g m^{-2}	0.77	2.64	1.65±0.57	1.22	2.55	1.72±0.29
Nitrogen	g m^{-2}	1.77	5.95	3.61±1.26	0.56	2.32	1.23±0.46
Canopy lignin	g m^{-2}	41.60	150.70	89.73±35.58	27.13	143.59	79.13±31.97
Canopy cellulose	g m^{-2}	66.70	241.10	147.76±52.77	37.23	192.95	107.64±42.34
EWT	g m^{-2}	46.15	165.63	99.90±35.16	24.00	114.73	63.95±25.18
Stem lignin	Kg m^{-2}	0.40	10.40	3.95±2.98	0.49	2.55	1.37±0.52
Stem Cellulose	Kg m^{-2}	1.30	12.60	5.81±3.42	0.72	3.76	2.17±0.77

Table 3.8a. Error in prediction of biophysical attributes of teak

Teak		Per unit area				% mean value			
		Full spectra		Subset		Full spectra		Subset	
Measurement unit	Biophysical attributes	SEC	SECV	SEC	SECV	SEC	SECV	SEC	SECV
t ha^{-1}	Bole biomass	27.60	34.99	27.70	35.10	21.85	27.70	21.93	27.79
m^2 0.1 ha^{-1}	Canopy area	75.42	98.00	86.28	131.31	13.28	17.25	15.19	23.12
-	LAI *	0.63	0.68	0.60	0.66	13.88	14.98	13.22	14.54

*** Results for LAI are coming from combined dataset of teak and bamboo.**

Table 3.8b. Error in prediction of biophysical attributes of bamboo

Bamboo		Per unit area				% mean value			
Measurement unit	Biophysical attributes	Full spectra		Subset		Full spectra		Subset	
t ha^{-1}	**Bole biomass**	2.82	4.91	4.87	5.34	4.64	8.08	8.01	8.79
m^2 0.1 ha^{-1}	**Canopy area**	78.25	87.13	79.72	92.52	15.08	16.79	15.36	17.83

Table 3.9. Error in prediction of biophysical attributes of mixed vegetation cover

Measurement unit	Biophysical attributes	R^2	SECV	% mean value
t ha^{-1}	**Bole biomass**	0.83	48.05	33.91
m^2 0.1 ha^{-1}	**Canopy area**	0.67	135.54	19.16

Table 3.10a. Error in prediction of biochemical attributes of teak

Teak		Per unit area				% mean value			
		Full spectra		Subset		Full spectra		Subset	
Measurement Unit	Biochemical attributes	SEC	SECV	SEC	SECV	SEC	SECV	SEC	SECV
g m^{-2}	**Chlorophyll**	0.19	0.26	0.18	0.21	11.52	15.76	10.91	12.73
g m^{-2}	**Nitrogen**	0.52	0.79	0.58	0.71	14.40	21.88	16.07	19.67
g m^{-2}	**Canopy Lignin**	13.96	18.93	14.94	16.64	15.56	21.10	16.65	18.54
g m^{-2}	**Canopy Cellulose**	28.64	33.13	26.07	31.13	19.38	22.42	17.64	21.07
Kg m^{-2}	**Stem Lignin**	1.45	1.58	1.16	1.52	36.71	40.00	29.37	38.48
Kg m^{-2}	**Stem Cellulose**	1.75	2.03	1.74	1.97	30.12	34.94	29.95	33.91
g m^{-2}	**EWT**	16.66	21.60	17.66	22.36	16.68	21.62	17.68	22.38

Table 3.10b. Error in prediction of biochemical attributes of bamboo

Bamboo		Per unit area				% mean value			
		Full spectra		Subset		Full spectra		Subset	
Measurement unit	Biochemical attributes	SEC	SECV	SEC	SECV	SEC	SECV	SEC	SECV
g m^{-2}	**Chlorophyll**	0.14	0.16	0.13	0.14	8.24	9.41	7.65	8.24
g m^{-2}	**Nitrogen**	0.24	0.29	0.26	0.28	19.51	23.58	13.46	22.76
g m^{-2}	**Canopy Lignin**	16.01	19.00	15.01	18.11	20.23	24.01	18.96	22.89
g m^{-2}	**Canopy Cellulose**	22.47	25.44	22.07	24.85	20.88	23.63	20.50	23.09
Kg m^{-2}	**Stem Lignin**	0.32	0.38	0.25	0.27	23.36	27.74	18.25	19.71
Kg m^{-2}	**Stem Cellulose**	0.46	0.54	0.45	0.48	21.20	24.88	20.74	22.12
g m^{-2}	**EWT**	13.12	15.94	13.12	15.94	20.52	24.93	20.52	24.93

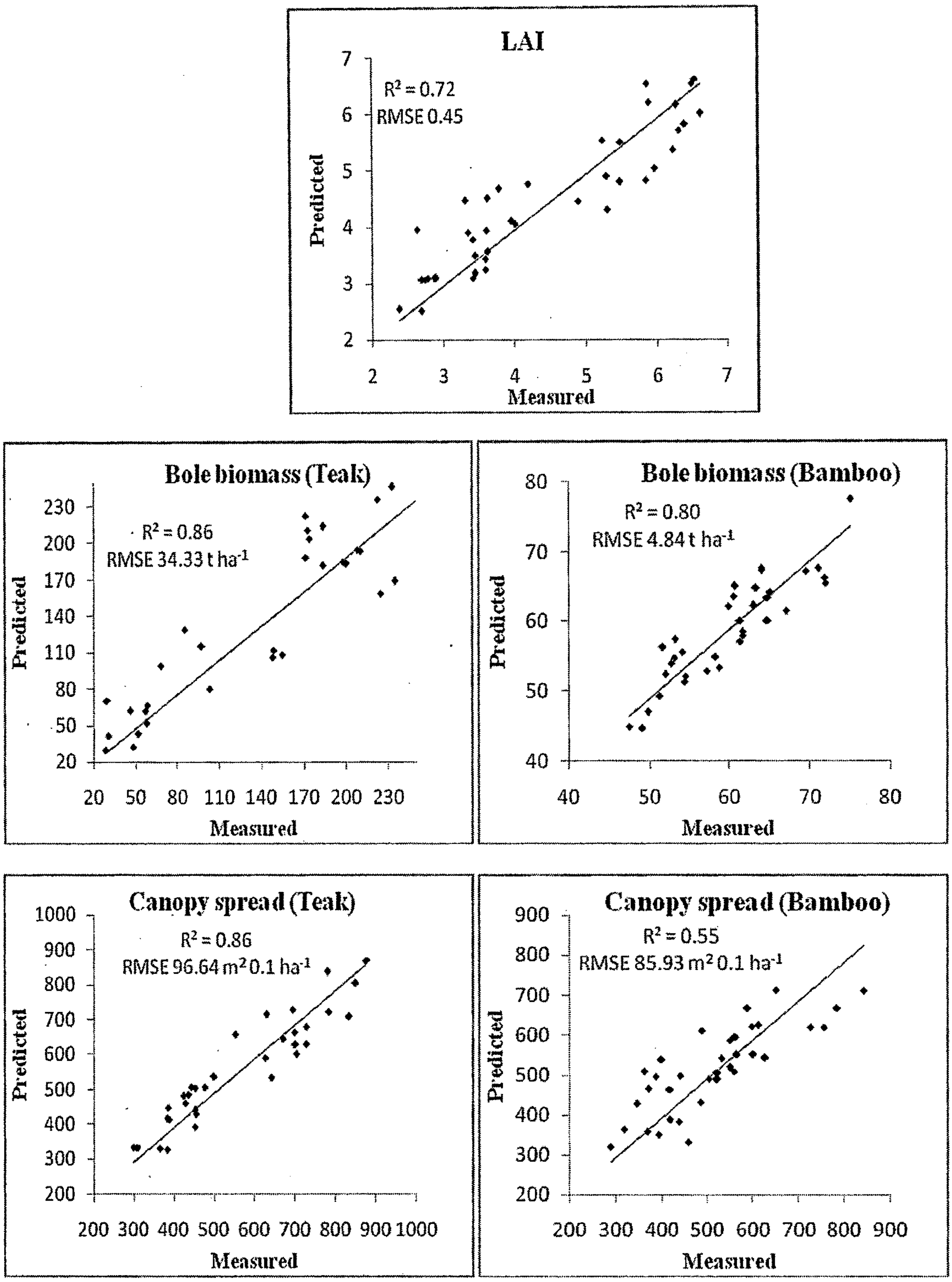


Figure 3.10. Measured and predicted biophysical attributes through PLS regression of full reflectance spectra (PLS regression models for Canopy spread was preared using October reflectance spectra while for all other biophysical parameters PLS models were prepared using April reflectance spectra)

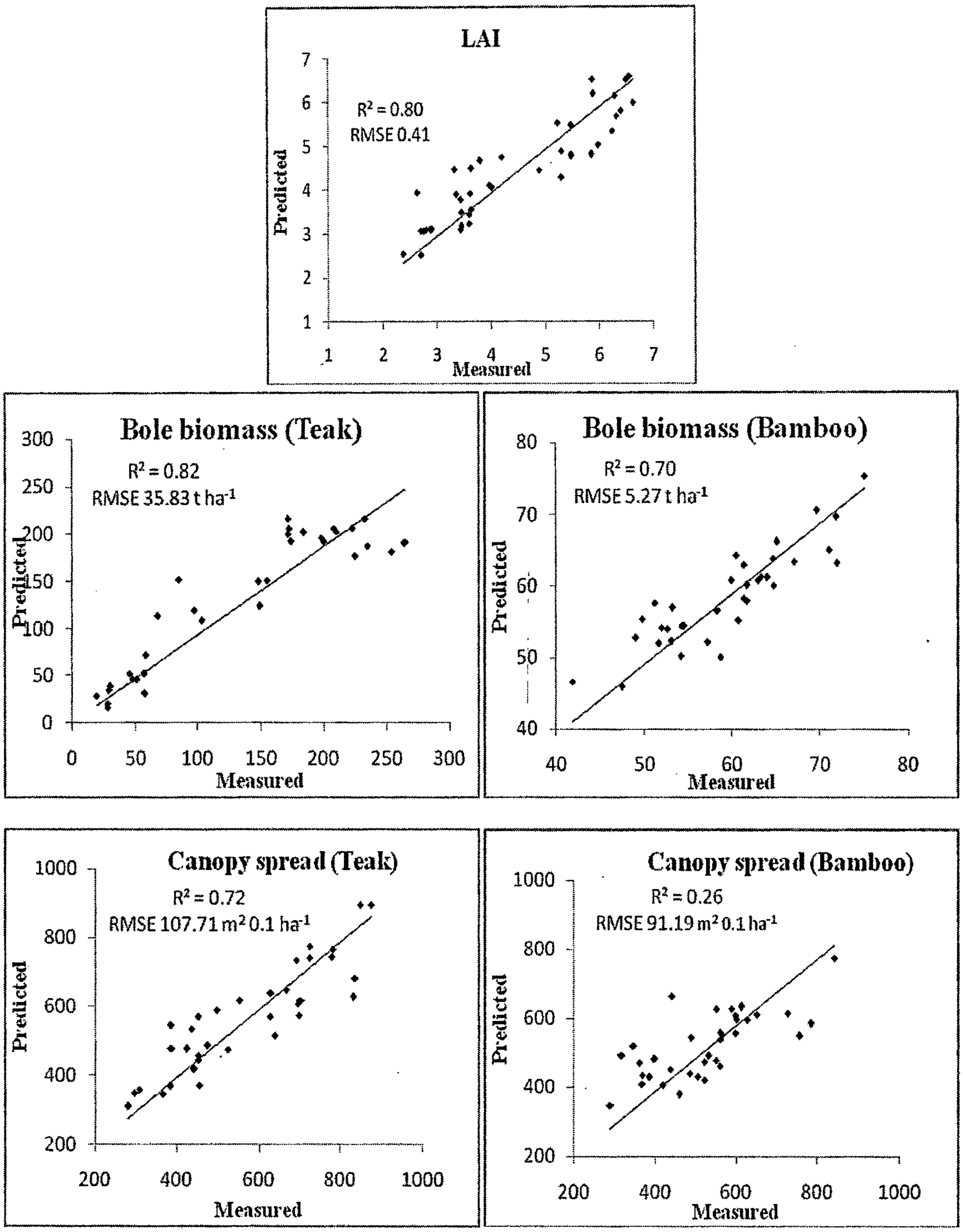
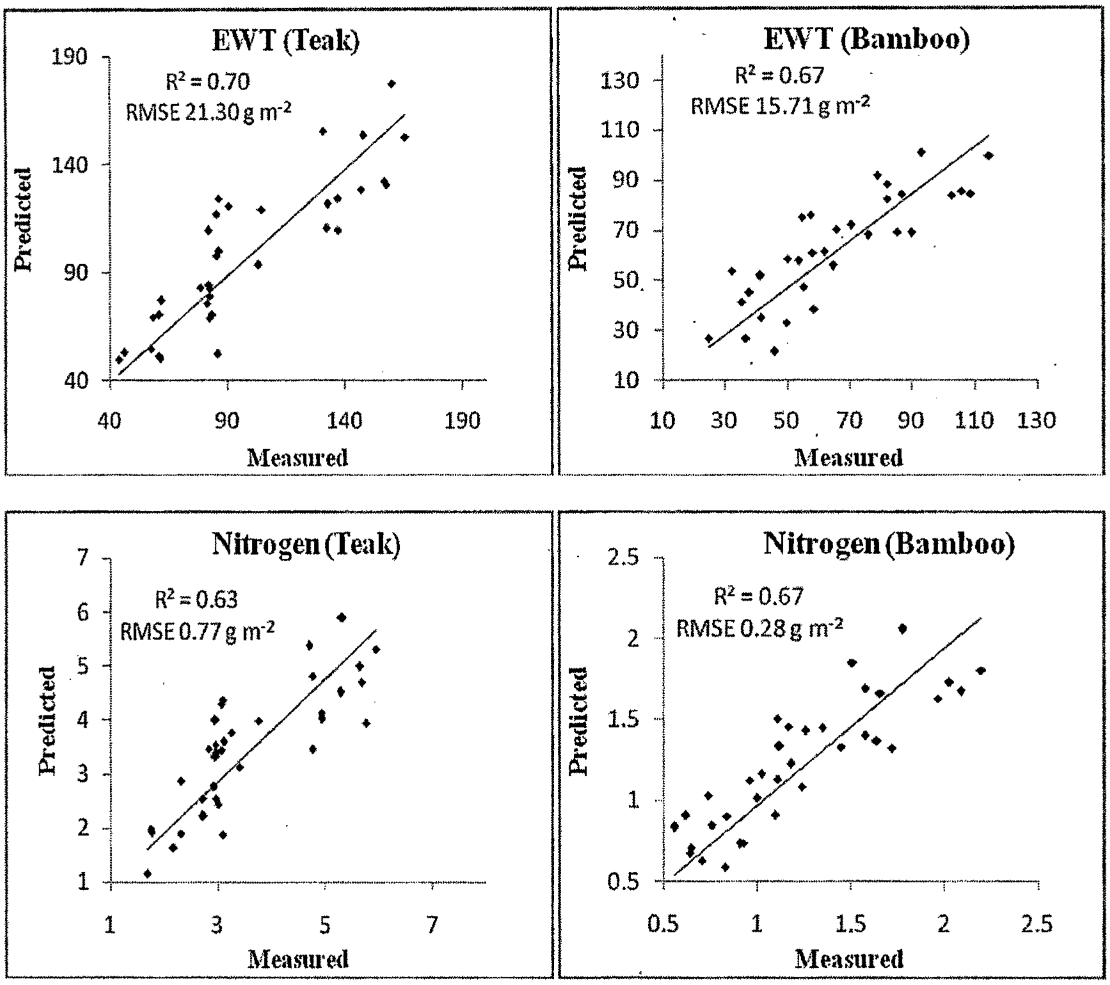
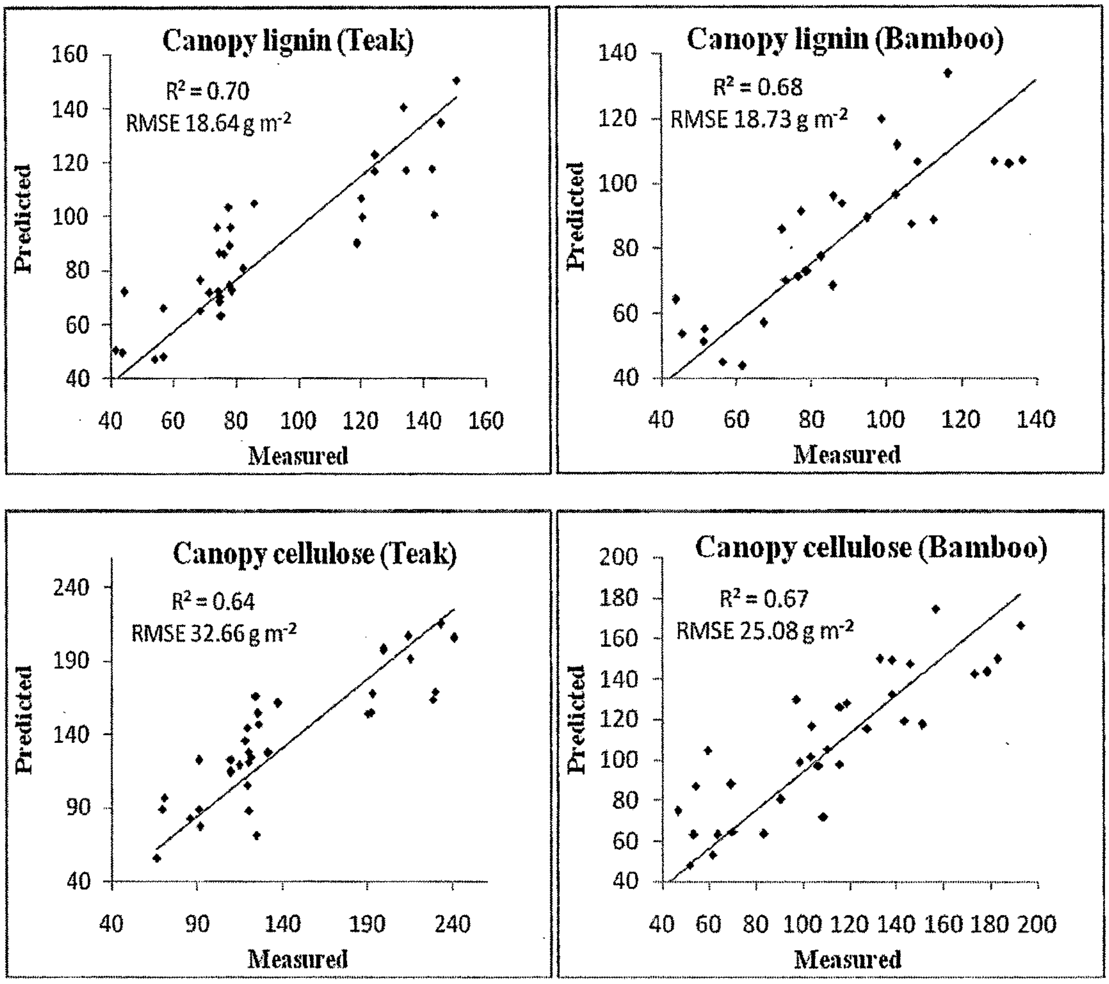


Figure 3.11. Measured and predicted biophysical attributes through PLS regression of spectral subset (PLS regression models for Canopy spread was preared using October reflectance spectra while for all other biophysical parameters PLS models were prepared using April reflectance spectra)


EWT (Teak)
$R^2 = 0.70$
RMSE 21.30 g m-2
Predicted
Measured
EWT (Bamboo)
$R^2 = 0.67$
RMSE 15.71 g m-2
Predicted
Measured
Nitrogen (Teak)
$R^2 = 0.63$
RMSE 0.77 g m-2
Predicted
Measured
Nitrogen (Bamboo)
$R^2 = 0.67$
RMSE 0.28 g m-2
Predicted
Measured

Continued……


Canopy lignin (Teak)
$R^2 = 0.70$
RMSE 18.64 g m^{-2}
Predicted
Measured
Canopy lignin (Bamboo)
$R^2 = 0.68$
RMSE 18.73 g m^{-2}
Predicted
Measured
Canopy cellulose (Teak)
$R^2 = 0.64$
RMSE 32.66 g m^{-2}
Predicted
Measured
Canopy cellulose (Bamboo)
$R^2 = 0.67$
RMSE 25.08 g m^{-2}
Predicted
Measured

Continued......

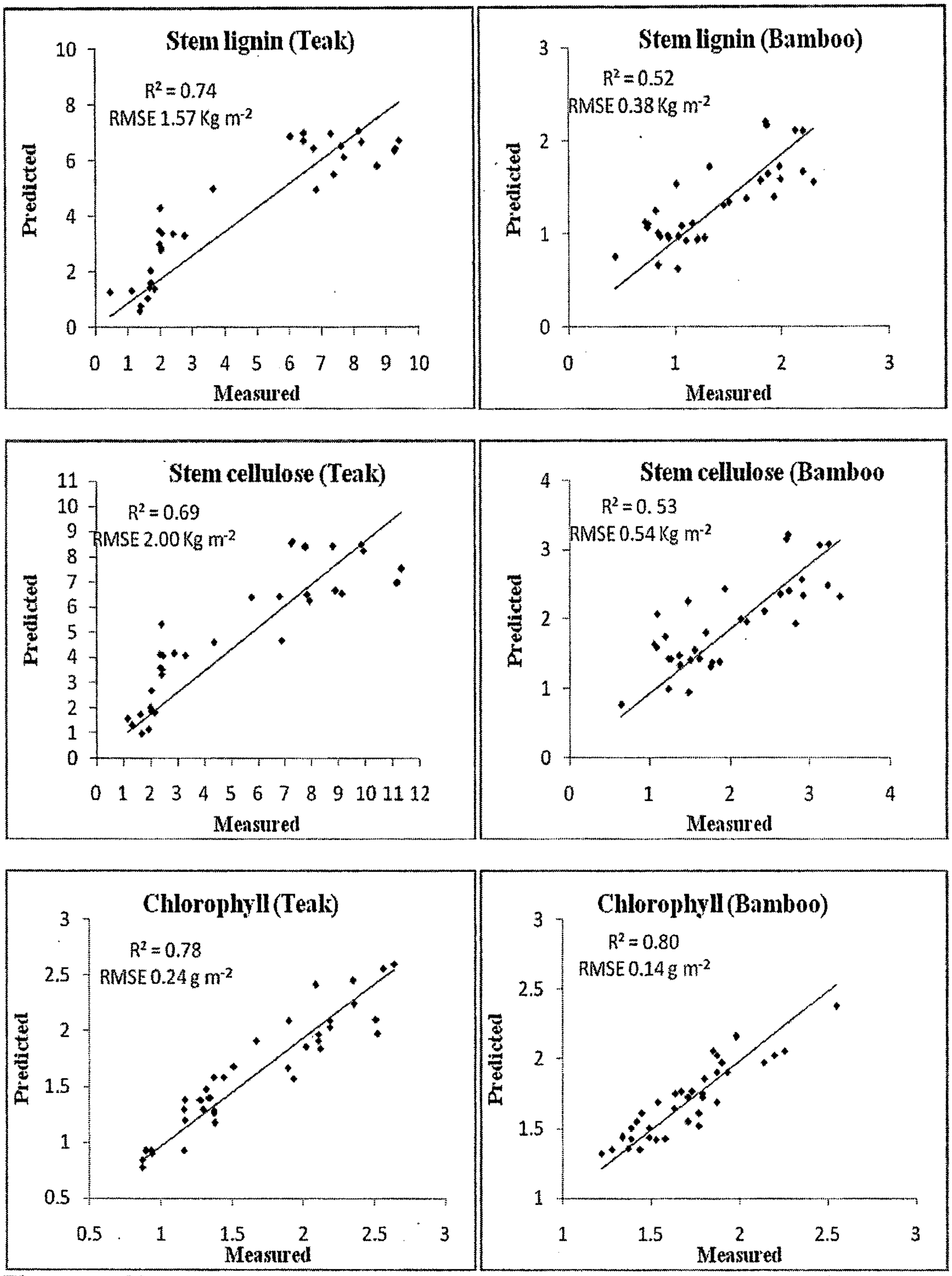
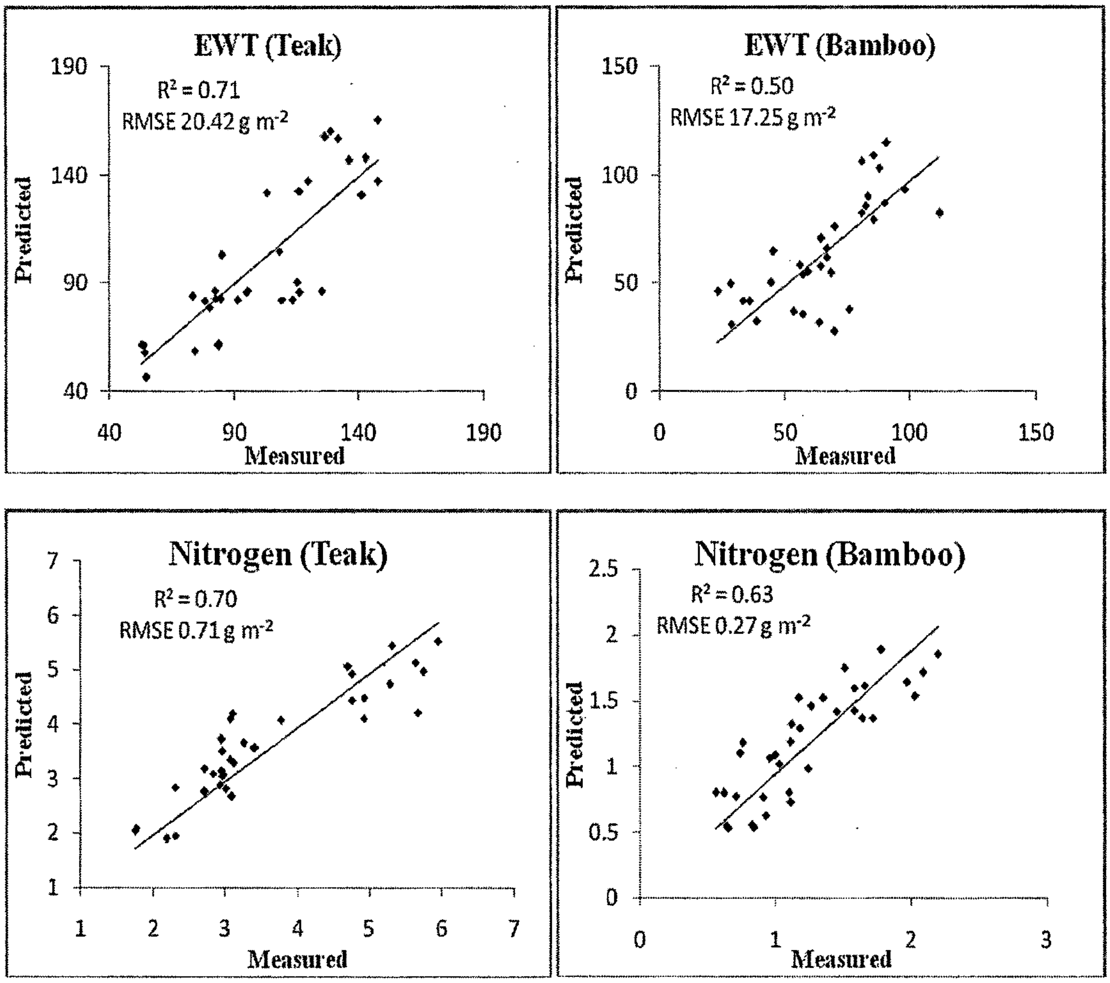
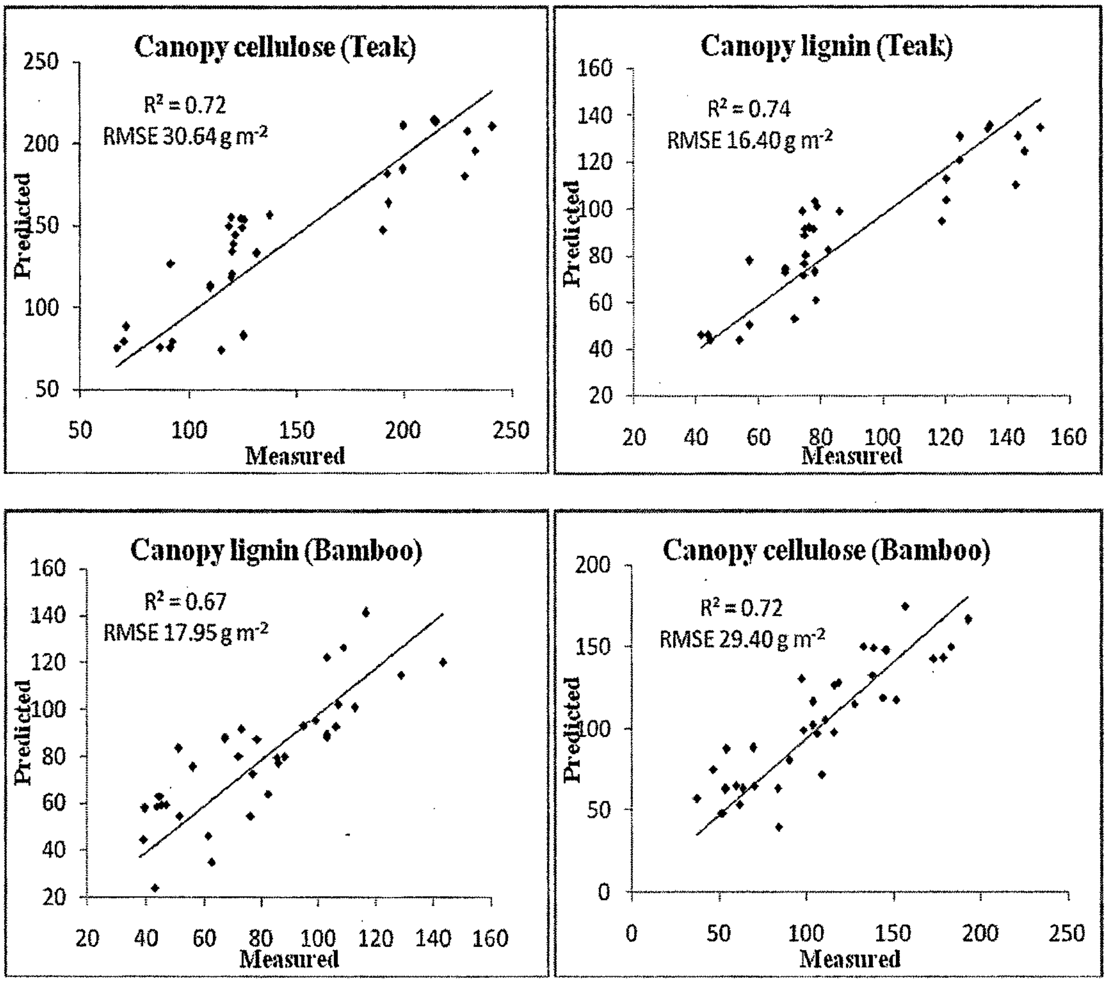


Figure 3.12. Measured and predicted biochemical attributes through PLS regression of full reflectance spectra (For stem lignin and cellulose PLS regression models prepared using April reflectance spectra, for all other biochemical parameters PLS models were prepared using October reflectance spectra)



EWT (Teak)
R² = 0.71
RMSE 20.42 g m-2
Predicted
Measured
EWT (Bamboo)
R² = 0.50
RMSE 17.25 g m-2
Predicted
Measured
Nitrogen (Teak)
R² = 0.70
RMSE 0.71 g m-2
Predicted
Measured
Nitrogen (Bamboo)
R² = 0.63
RMSE 0.27 g m-2
Predicted
Measured

Continued.......


Canopy cellulose (Teak)
$R^2 = 0.72$
RMSE 30.64 g m^{-2}
Predicted
Measured
Canopy lignin (Teak)
$R^2 = 0.74$
RMSE 16.40 g m^{-2}
Predicted
Measured
Canopy lignin (Bamboo)
$R^2 = 0.67$
RMSE 17.95 g m^{-2}
Predicted
Measured
Canopy cellulose (Bamboo)
$R^2 = 0.72$
RMSE 29.40 g m^{-2}
Predicted
Measured

Continued.......

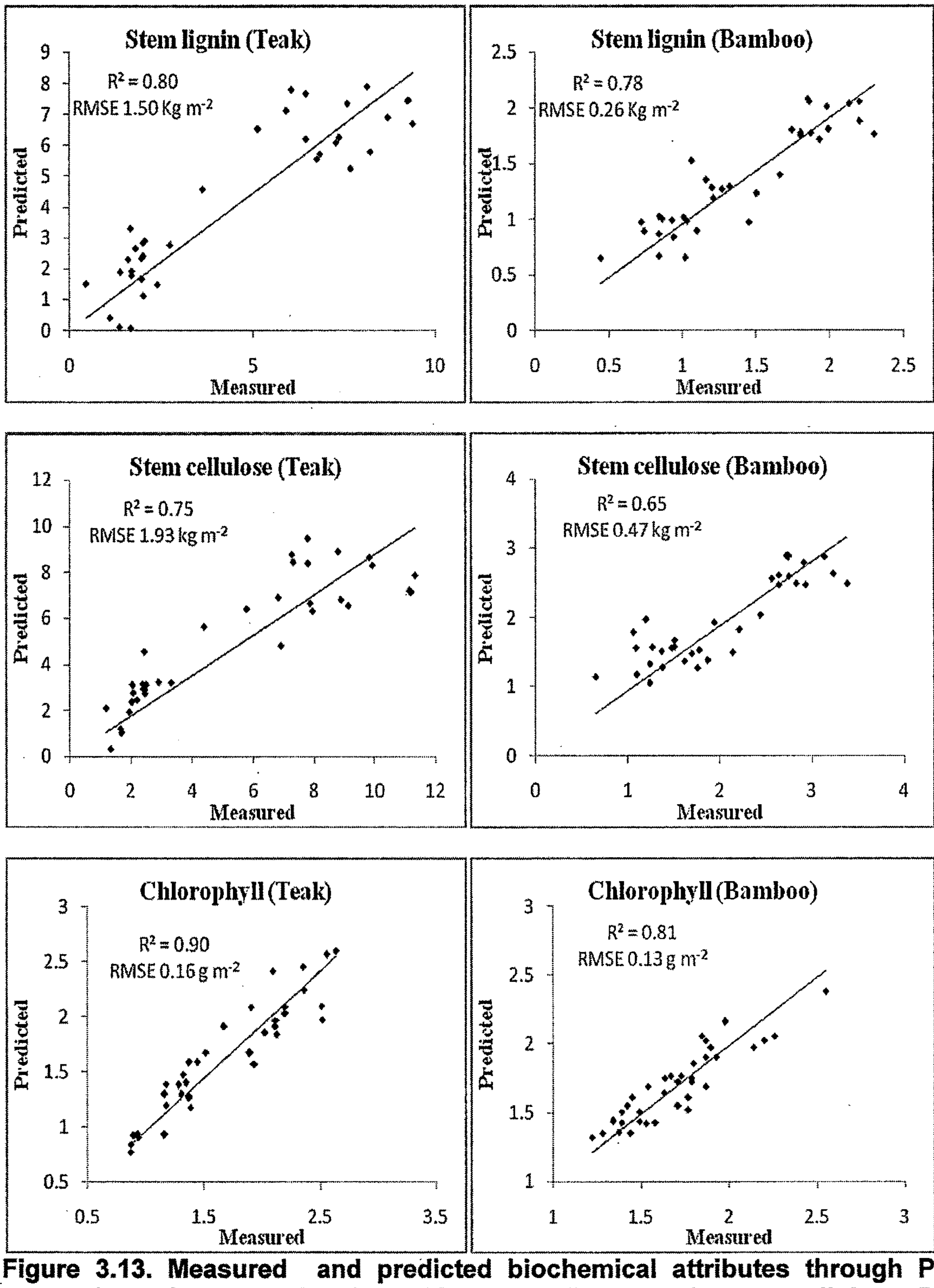


Figure 3.13. Measured and predicted biochemical attributes through PLS regression of spectral subset (For stem lignin and stem cellulose PLS regression models prepard using April reflectance spectra, for all other biochemical parameters PLS models were prepared using October reflactance spectra)

3.6 Devlopment of vegetation indices

PLS regression model for prediction of chlorophyll showed maximum negative coefficient (Vyas et al. 2012). These two wavelengths (692 and 743nm were selected for developing ratios for chlorophyll estimation **(Table 3.11)**. Simple ratio (743/692) gave best results for prediction of chlorophyll with Leave One Out Cross Validation (LOO-CV) (R^2 0.73, RMSE 0.28 for Teak, R^2 0.71, RMSE 0.15 for Bamboo) **(Figure 3.14 a,b)**. Root Mean Square Error (RMSE) values of this study are lower for both the species mentioning about higher accuracy of the developed ratio in chlorophyll estimation. The best PLS regression model for prediction of LAI showed maximum negative coefficient at 1457nm and maximum positive coefficient value at 1084nm **(Figure 3.14c)**. These two wavelengths (1084 and 1457 nm) were selected to develop ratios for LAI estimation. **Table 3.11** shows developed vegetation indices for LAI. Normalized difference ratio (ND1457/1084) gave the best results for prediction of LAI with LOO-CV method (R^2 0.66, RMSE 0.57). **Table 3.12** show comparison of performance between vegetation indices developed in present study and number of indices developed by other researchers.

Table 3.11. Developed vegetation indices for measured parameters

Index	Data set	Parameter
743/692	Teak	Chlorophyll (g m^{-2})
743/692	Bamboo	Chlorophyll (g m^{-2})
ND 743/692	Teak	Chlorophyll (g m^{-2})
ND 743/692	Bamboo	Chlorophyll (g m^{-2})
1457/1084	(Teak +Bamboo)	LAI
ND 1457/1084	(Teak +Bamboo)	LAI

Table 3.12. Comparison of developed indices with other published indices

Developed indices	Data set	Parameter	Remote sensing data	Lowest % RMSE (per mean value)	Reference
SR 743/692	Teak	Chlorophyll	Spaceborne	16.57	Present study
SR 743/692	Bamboo	Chlorophyll	Spaceborne	9.49	Present study
ND 1457/1084	Teak +Bamboo	LAI	Spaceborne	13.57	Present study
MCARI/OSAVI 750,705 *	Temperate vegetation stands	Chlorophyll	Spaceborne	30.53	Wu et al. 2010
MCARI II 750,705#	Temperate vegetation stands	LAI	Spaceborne	32.73	Wu et al. 2010
ND 925/710	Temperate vegetation stands	Chlorophyll	Spaceborne	17.33	le Maire et al. 2008
Derivative index 1725-970	Temperate vegetation stands	LAI	Spaceborne	31.19	le Maire et al. 2008
SR 753/710	Pinus stands	Chlorophyll	Airborne	19.37	Zarco-Tejada et al. 2004
PVI 1088/1148**	Temperate vegetation stands	LAI	Airborne	21.29	Schlerf et al. 2005
ND 1141/1150	Heterogeneous Grass land	chlorophyll	Airborne	40.12	(SR= et Darvishzadeh et al.2008
SR 750/445	Temperate tree species	Chlorophyll	Leaf level	4.28	ims and Gamon 2002

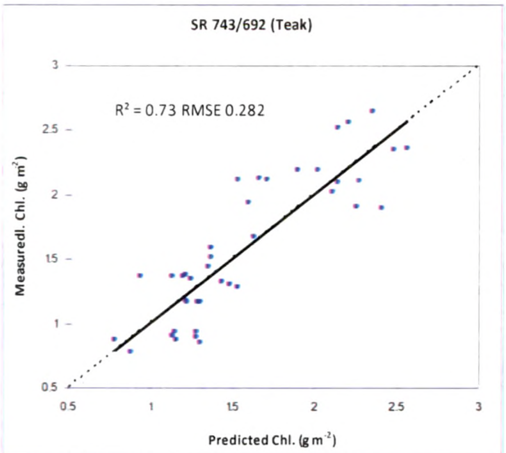
(SR=simple ratio, ND=Normalized difference)

*Modified Chlorophyll Absorption Ratio Index/Optimized Soil-Adjusted Vegetation Index (for details see the reference)

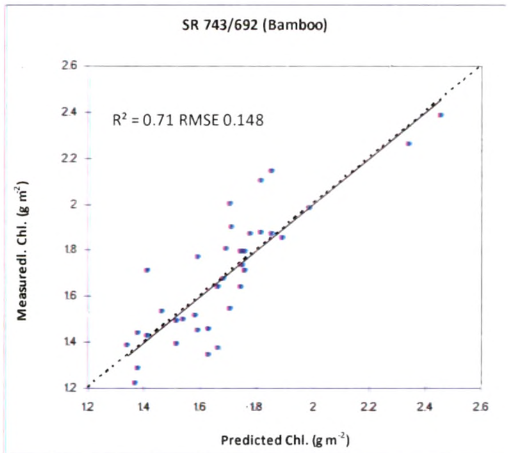
#Modified Chlorophyll Absorption Ratio Index II (for details see the reference)

** Perpendicular vegetation index

(a.)



(b.)



(c.)

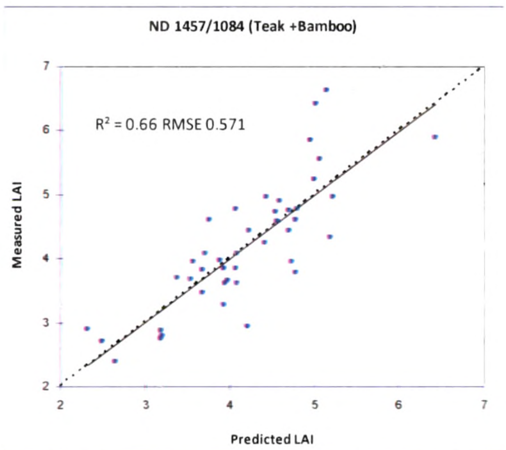
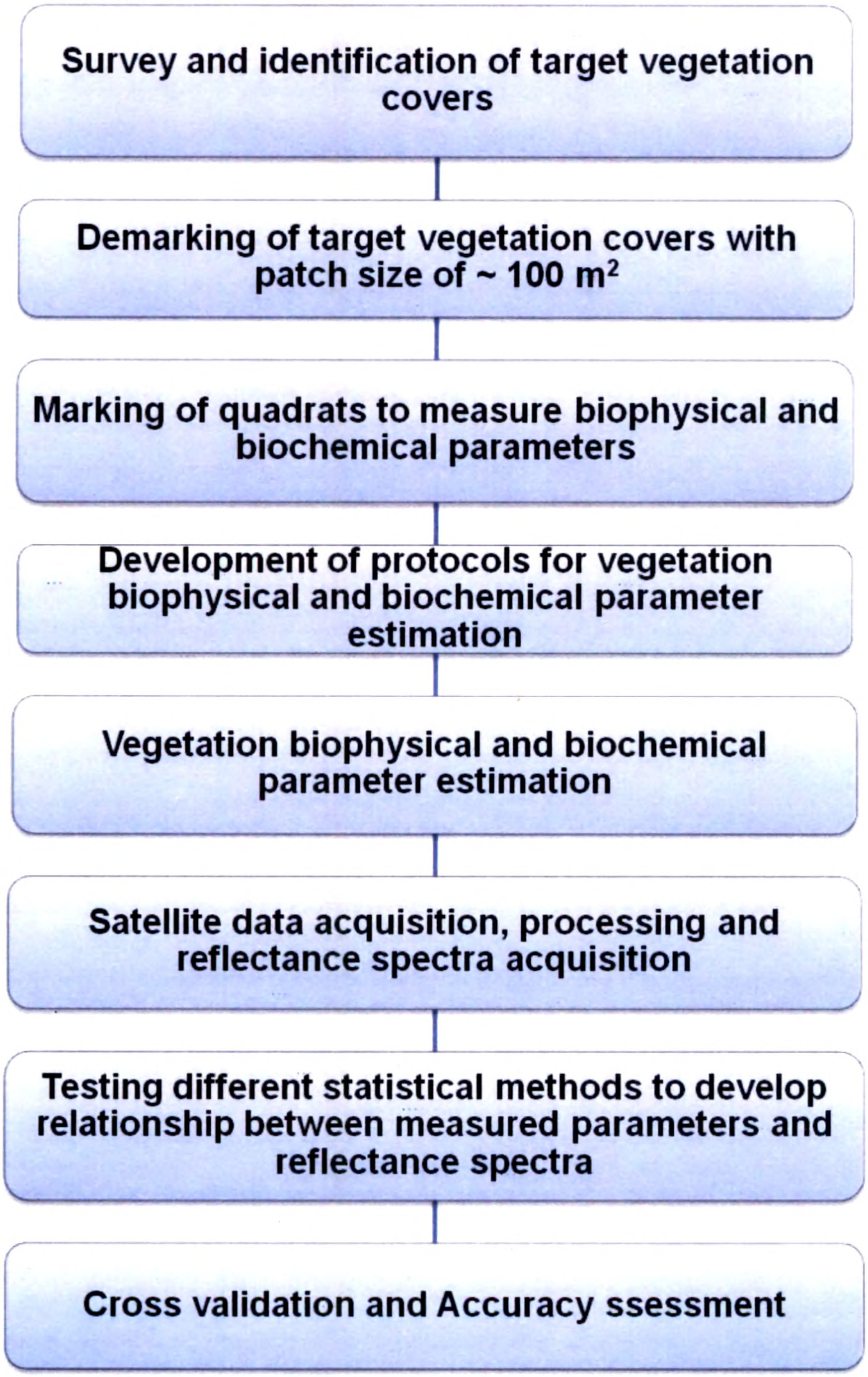


Figure 3.14. Cross-validated prediction of Chlorophyll and LAI by leave one out method using best performing developed indices. (a.) LOO-CV for developed vegetation index 743/692 for Teak (b.) LOO-CV for developed vegetation index 743/692 for Bamboo (c.) LOO-CV for developed vegetation index 1457/1084

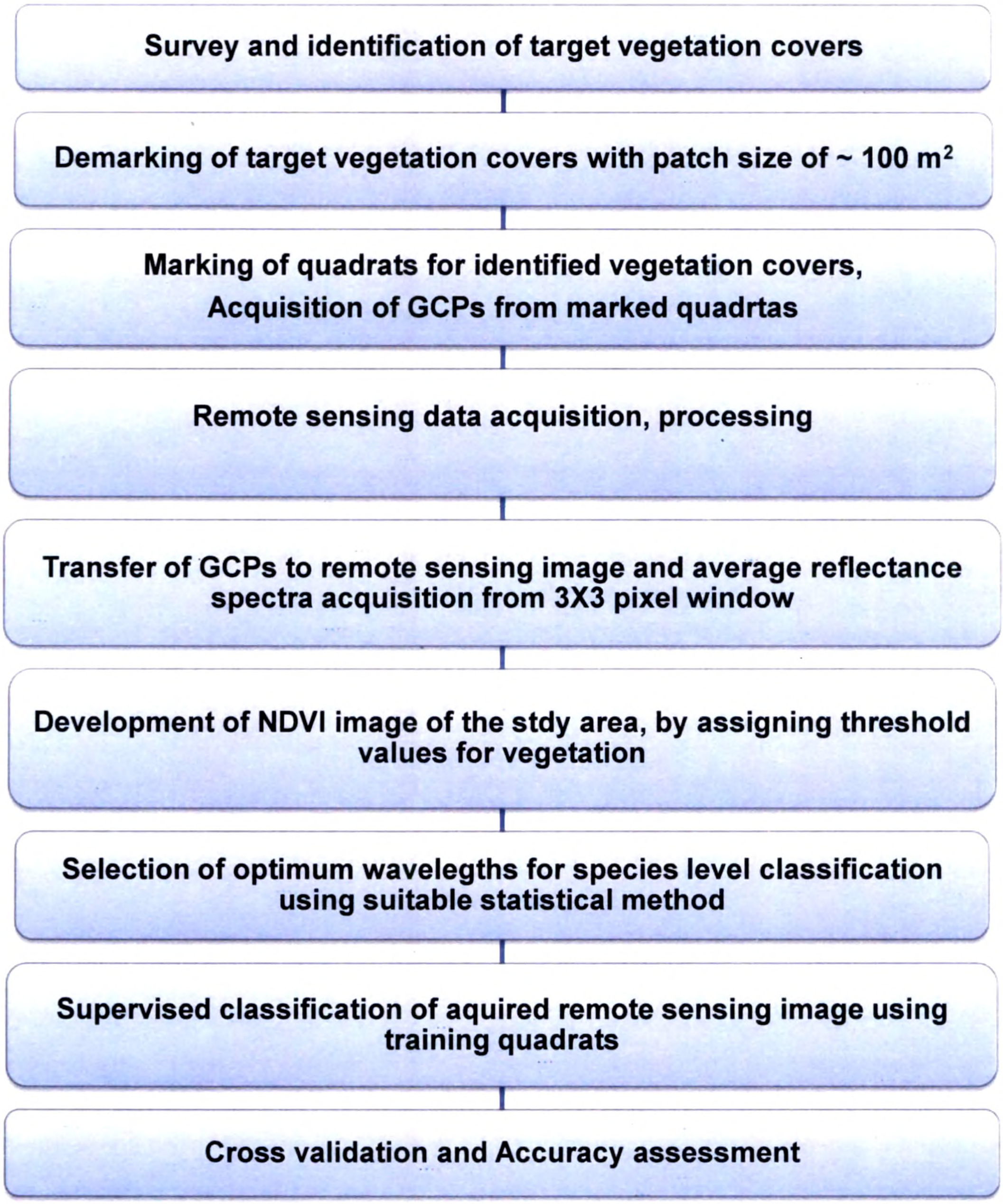
3.7 Development of algorithms

PLS regression models were developed for estimation of biophysical and biochemical attributes of teak and bamboo using space borne (Hyperion EO-1) reflectance data. All the steps for model development were systematically put together and algorithms were developed for estimation of biophysical and biochemical attributes of teak and bamboo. Flow chart given below shows different steps that lead to the estimation of biophysical and biochemical parameters of teak and bamboo vegetation covers. Flow chart shows hierarchy of different commands that are essential for accurate estimation of biophysical and biochemical attributes of teak and bamboo using space borne reflectance data. First step and second step point out importance of detailed ecological survey of the selected study area. Both step illustrate the importance of Information about ecological features of vegetation covers and its distribution pattern. Third step illustrate that quadrats should be marked according to spatial resolution of sensor to be used. Fourth and fifth steps illustrate the importance of standardization of protocols for biophysical and biochemical parameter estimation. Protocols should be standardized on the basis of size of the study area, density of individuals, canopy area and distribution of individuals in the study area. Sixth and seventh steps indicate importance of identification of appropriate methods for modeling of relationship between measured biophysical and biochemical parameters and acquired reflectance spectra from hyperspectral sensor. In present study it was found that Partial least square (PLS) regression worked as better technique for modeling of relationship between biophysical and biochemical parameters and Hyperion reflectance spectra. For validation of developed model, cross validation techniques should be used for comparison between actually measured and estimated variables. In this study Leave one out cross validation (LOO-CV) technique has been used for comparison between measured and estimated variables. Following flow charts show steps of algorithms developed for biophysical and biochemical parameter estimation.

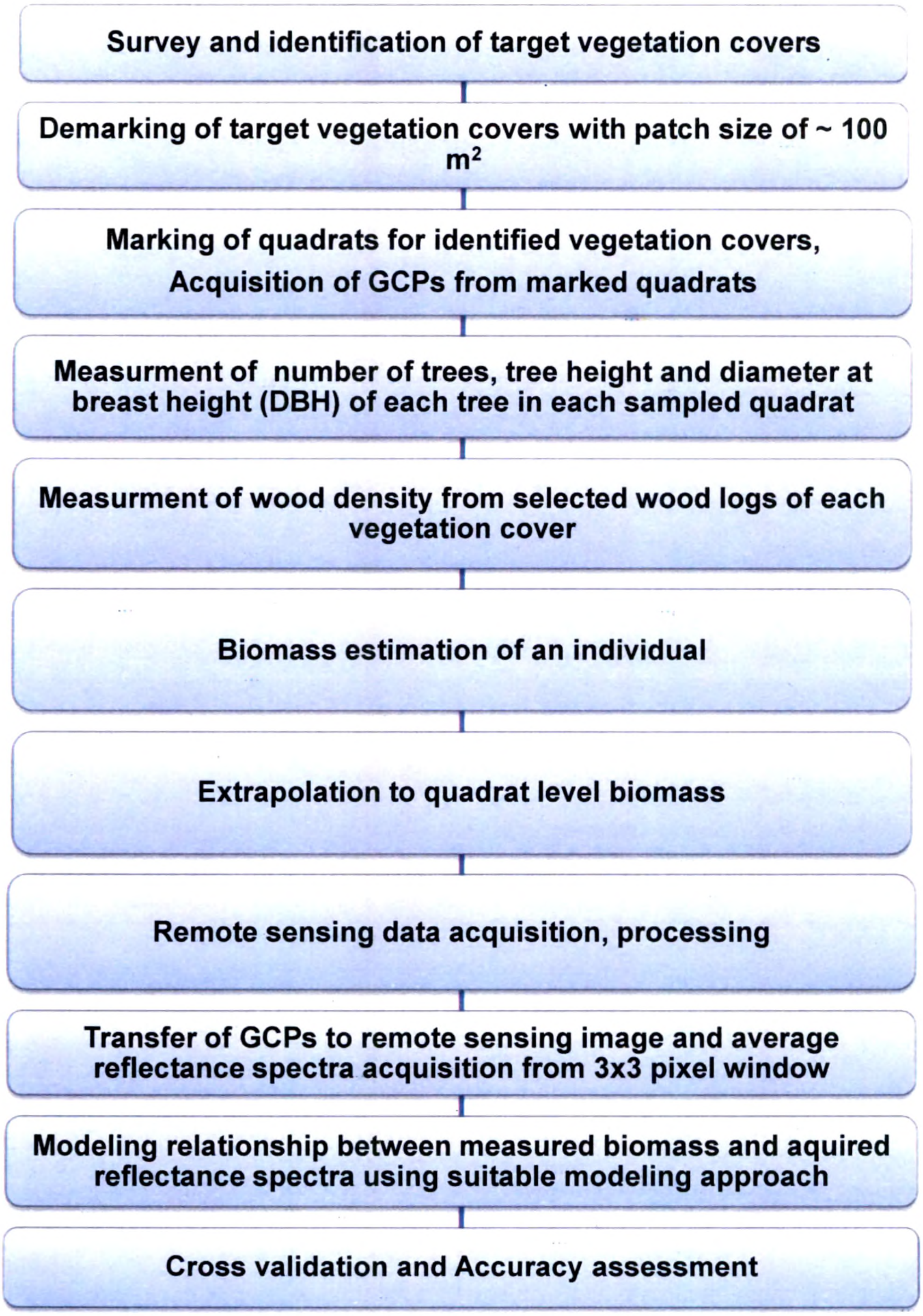
General steps for biophysical and biochemical parameter estimation



Species level classification



Biomass estimation



Biochemical parameter estimation

Survey and identification of target vegetation covers

Demarking of target vegetation covers with patch size of ~ 100 m^2

Marking of quadrats for identified vegetation covers,
Acquisition of GCPs from marked quadrats

Foliage collection randomly from different parts of the canopy and canopy area and number of trees measurment from each sampled quadrat

Collected leaf samples were oven dried at 70 C for 48 hours and grinded. Dried leaf powder used for the estimation biochemical parameters

Extrapolation of canopy level measurment to quadrat level biochemical parameters

Remote sensing data acquisition, processing

Transfer of GCPs to remote sensing image and average reflectance spectra acquisition from 3x3 pixel window

Modeling relationship between measured biochemical parameetrs and aquired reflectance spectra using suitable modeling approach

Cross validation and Accuracy assessment

3.8 Laboratory reflectance spectra

Average reflectance spectra acquired in the laboratory for teak, bamboo and few other species were shown in **Figure 3.15.** Leaf thickness readings along with number of palisade and spongy tissue layers for all the five species were shown in **Table 3.13**. Measured total chlorophyll, chlorophyll a and b values were given in **Table 3.14.** Leaf thickness clearly effected reflectance values of NIR region (700-1300 nm). Reflectance of NIR region was proportional to leaf thickness. Teak showed highest leaf thickness and maximum reflectance in NIR region. **Figure 3.16a and 3.16b** show average Hyperion reflectance spectra and average laboratory reflectance spectra for teak, bamboo and some mixed vegetating cover species.

Longitudinal section (L.S) of *Tectona* and *Ficus* leaf showed 2 layers of pallisade tissue. L.S of *Madhuca* leaf showed single layer of pallisade tissue. However, pallisade layer in *Madhuca* leaf was relatively longer. L.S of *Mangifera* leaf showed single layer of palisade tissue **(Figure 3.17)**. Results for SDA analysis were given in **Table 3.15.** SDA identified 10 wavelengths from laboratory spectra of five selected species showing variation in reflectance values. Of the 10 identified wavelengths, five came from visible region, three from NIR region and two bands from SWIR region.

Measured total chlorophyll values are ranging from minimum of 18.20 to maximum of 53.95 µg cm^{-2}. Measured chlorophyll a values are ranging from minimum of 15.50 to maximum of 43.20 µg cm^{-2} . Measured chlorophyll b values are ranging from minimum of 1.35 to maximum of 9.00 µg $cm^{-2.}$ Regression coefficients (R^2) generated by all tested indices for measurement of total chlorophyll, chlorophyll a and b were shown in **Table 3.16**. Results indicate that red edge index developed by Vogelmann et al. (1993) that is Red edge 740~ 720 gave highest R^2 vales for estimation of total chlorophyll (R^2 0.77) and chlorophyll a (R^2 0.60). Followed by ZTM index developed by Zarco Tejada et al. (2001) and Red Edge index 750~700 developed by Gitelson and Merzylak (1997). Index developed in present study (SR 743/692) for estimation of total chlorophyll at stand level (using space borne reflectance spectra) also performed well for estimation of total chlorophyll from laboratory spectra (R^2 0.73). All tested indices were failed to achieve high R^2 values for estimation of chlorophyll b.

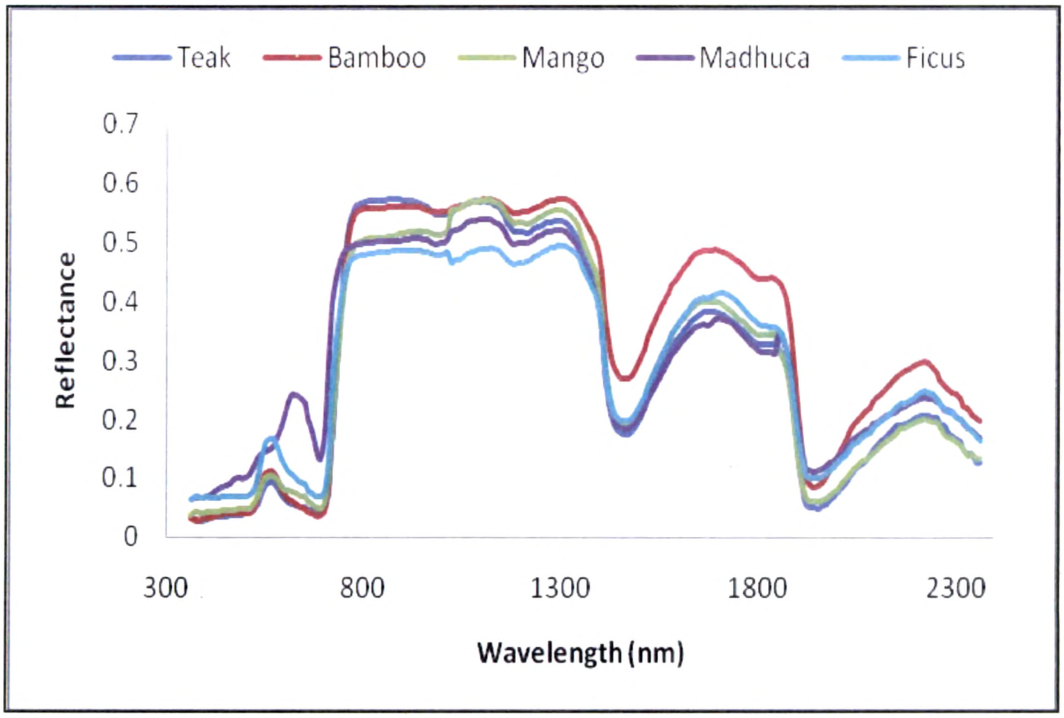


Figure 3.15. Average Laboratory reflectance spectra for selected species

Table 3.13. Thickness of leaves for species selected for Laboratory spectra acquisition

Species name	Leaf thickness (μm)
Tectona	266.35
Dendrocalamus	90.46
Madhuca	235.25
Mangifera	177.51
Ficus	233.67

Table 3.14. Measured biochemical attributes for species selected for Laboratory spectra acquisition

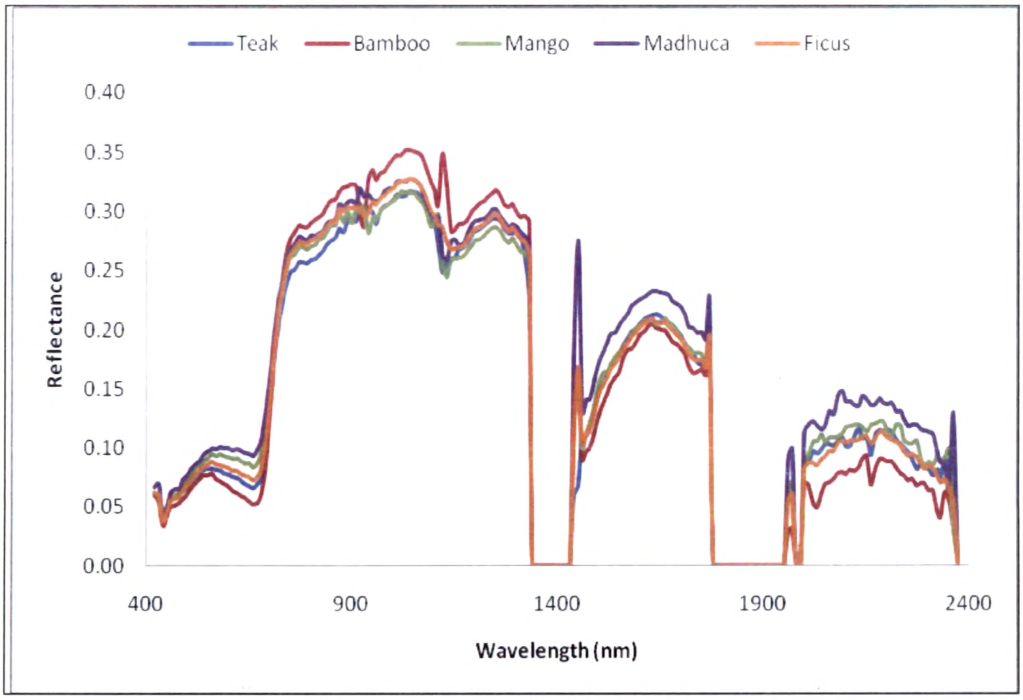
Leaf biochemical attributes		n=15		
		Minimum	Maximum	Mean
Total Chlorophyll	µg cm^{-2}	18.20	53.95	37.29±10.95
Chlorophyll a	µg cm^{-2}	15.50	43.20	27.65±8.11
Chlorophyll b	µg cm^{-2}	1.35	9.00	2.58±2.37

Table 3.15. Discrimination analysis (DA) between leaf level reflectance spectra
(Tectona,Dendrocalamus,Mangifera,Madhuca,Ficus)

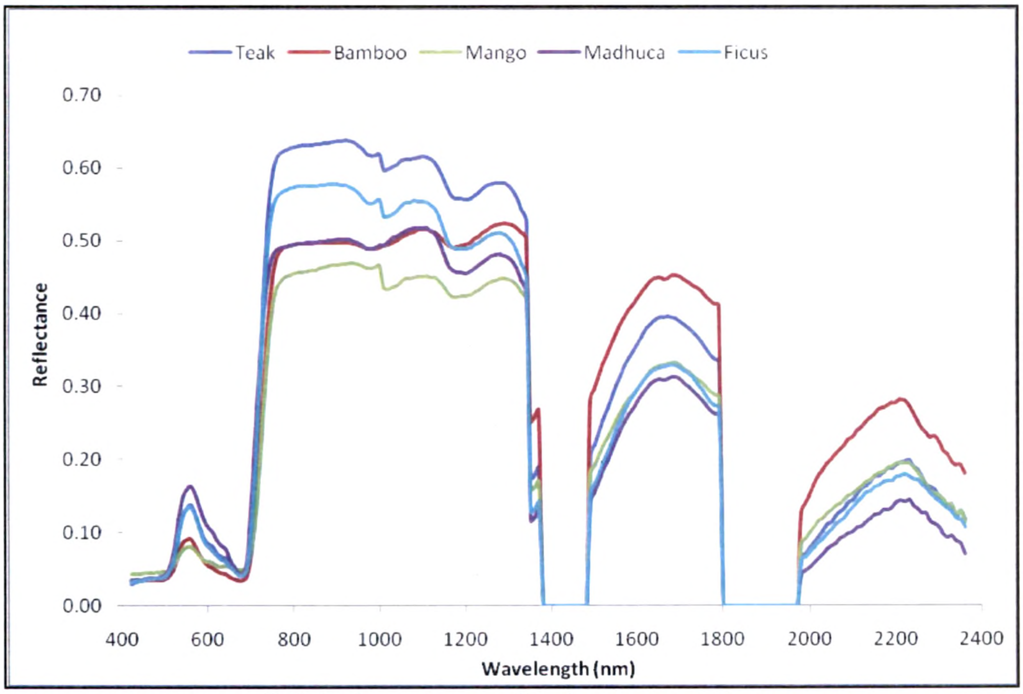
Wavelength (nm)	Wilks' Lambda
2150	0.105
410,2150,	0.110
410,550,2150	0.003
410,550,670,2150	0.0001
410, 520,550, ,670,710,2150	0.0001
410,520,550,670,710,870, 2150	0.0001
410,520,550, 670,710,730,870, 2150	0.0001
410,520,550, 630,670,710,730,870, 2150	0.0001
410,520,550, 630,670,710,730,870,2060, 2150	0.0001

Table 3.16. Performance of different indices for estimation of total chlorophyll, Chlorophyll a and b from laboratory spectra.

	Total chlorophyll ($\mu g\ cm^{-2}$)	Chlorophyll a ($\mu g\ cm^{-2}$)	Chlorophyll b ($\mu g\ cm^{-2}$)
		(R^2)	
RE740-420	0.77	0.60	0.31
ZTM	0.77	0.60	0.29
RE750-700	0.73	0.57	0.32
743/692 (From present study)	0.64	0.45	0.24
MSAVI	0.56	0.40	0.26
SAVI	0.55	0.40	0.27
RDVI	0.55	0.40	0.27
MSR	0.54	0.41	0.19
OSAVI	0.54	0.39	0.27
SIPI	0.54	0.37	0.24
NDVI	0.53	0.38	0.27
NPCI	0.52	0.41	0.23
MCARI2	0.49	0.34	0.31
MCARI1	0.47	0.34	0.31
TVI	0.45	0.33	0.29
TCARI	0.00	0.00	0.13



(a.) Hyperion reflectance spectra



(b.) Laboratory reflectance spectra

Figure 3.16. Comparison between laboratory spectra with Hyperion reflectance spectra of same species (Few bands were removed from laboratory spectra for exact comparison of laboratory spectra with Hyperion reflectance spectra)

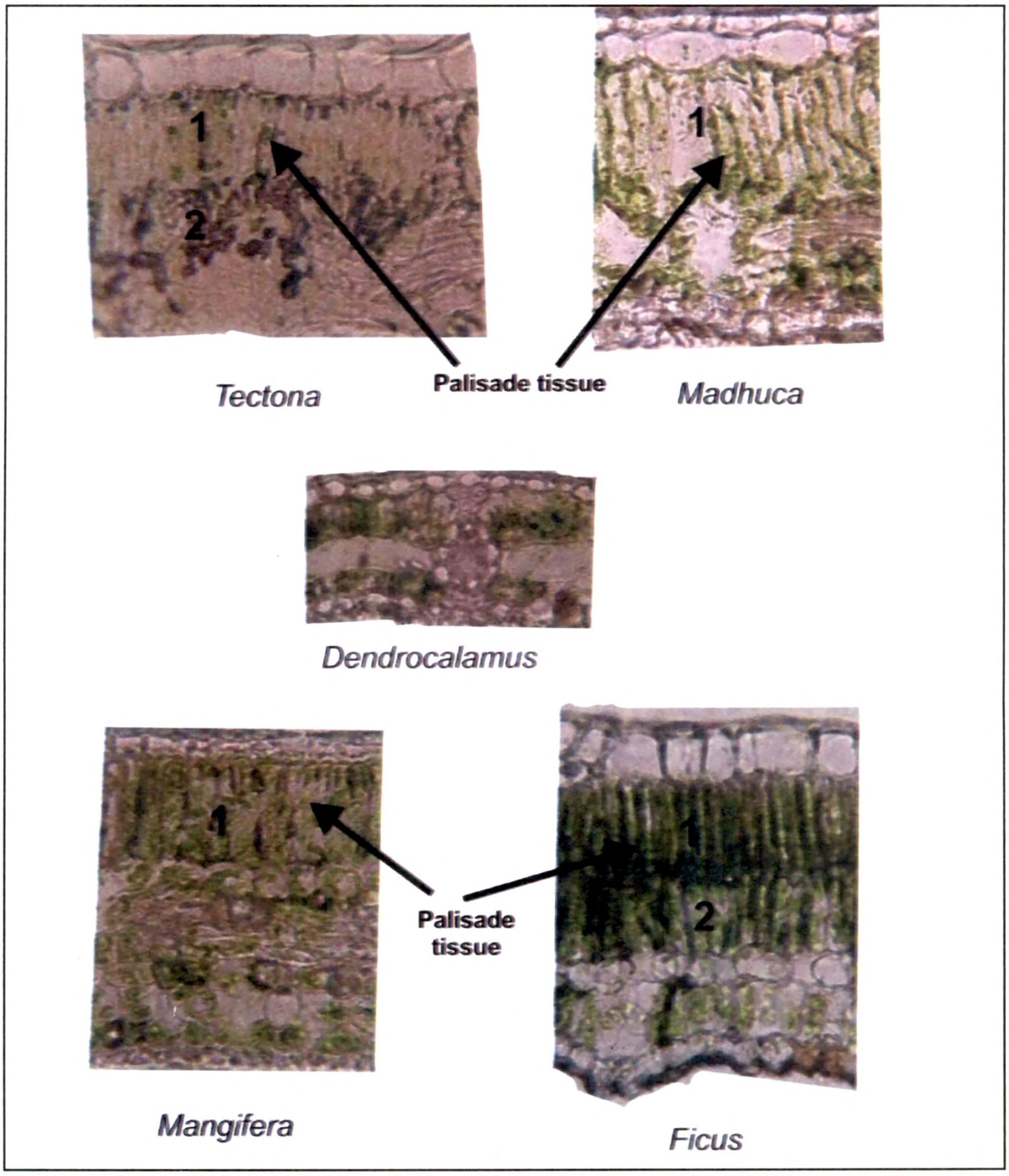


Figure 3.17. Leaf anatomical structures for species selected for Laboratory spectra acquisition