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Ecological Study of Aboveground Biomass and Plant Species Diversity in Complex Agroforestry Sites, Lampung, Indonesia

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Abstract. It is necessary to estimate the total carbon of forest or agroforest biomass using satellite remote sensing technology since the areas of Indonesian forests and agroforest are very large. However, ground truthing a large area would be time consuming and expensive; and the results might be affected by changes in the vegetation structure over the duration of the survey. Moreover, this method was also effective in monitoring changes in biomass and carbon by year. This study was therefore critical due to the lack of similar studies in Indonesia, especially on Sumatera Island. This study has the puspose to estimate the total biomass and biodiversity value in Damar agroforest; and investigate the relationship between the carbon stock in agroforest biomass and the pixel value, and continued mapping the carbon. In addition, simple linear regression and multiple linear regression were applied to analyse the single spectral band ratios of 1 to 5 and 7; and it also applied the 10 vegetation indices such as Simple Ratio 4/3, NDVI, SAVI, Brightness, Greenness, Wetness, TNDVI, ND 73, Simple Ratio 7/3, and Ratio 327 as a biomass predictor. The results have found that the dominating species (51 %) was Shorea javanica belonging to the family of Dipterocarpaceae. In addition, 73 species belonging to 35 families were identified. Biodiversity was identified to be moderately stable and the distribution of species abundance falls in the moderate category. Thus 70 % of Damar agroforest areas might be dominated by one or more species. The significant model was successful in finding in spectral reflectance at band 7. In addition, the model based on simple linear regression produced of R2 = 0.44; F-stat. = 14.88 > F crit. = 4.38, p-value = 0.001, df = 1, 19; and the model has the lowest value of RMSE = 52.84. This model was chosen as the ideal model to predict a carbon content in Damar agroforest with equation Y = 267.83 – 1625.5 band 7. The average carbon content was estimated to be 130.19 Mg C/ha, such carbon content was nearly equal to that of Dipterocarp forest. It is therefore important to maintain the Damar agroforest ecosystem services with high biodiversity as well as natural forest; furthermore, it is also a preferable site for carbon trading.

1. Introduction

The function of agroforestry and forest land use systems have become an important issue for further research under the afforestation and reforestation activities of the Kyoto Protocol [1]. However, plant biomass constitutes a significant carbon stock and is the main conduit for CO_2 removal from atmosphere primarily through photosynthesis. For this reason, the UNFCC and its Kyoto Protocol has recognised the role of forest in carbon sequestration. Different approach based on field measurements, confirmed that remote sensing and GIS have been applied for aboveground biomass estimation [2].

The conventional method based on field measurements are the most accurate but prove to be very costly and time consuming [3]. The use of remote sensing technique is reliable to be implemented especially on large area such as agroforests and forests in Indonesia. Thus the more challenging issue of carbon sequestration method is required in the area of wider spatial scale. Despite the importance of remote sensing data for estimating forest biomass/carbon, ground data are still necessary to develop the biomass predictive model and its validation, since remote sensing does not measure biomass, but rather it measures some other forest characteristics (e.g. spectral reflectance from the canopy)

The challenge use of remote sensing technology to estimate biomass is still widely open along with the launching of new different images with different resolutions and capabilities [2]. Recently, this is the most effective method to estimate the carbon stock in terms of time and budget. Remote sensing data are usually used to estimate land cover although it was being essentially used as an interpretation of images. It is usually necessary to validate the data against ground truth for accurate interpretation [4]. Satellite data have many potential capabilities for vegetation mapping and it was successful in estimating a quantitative ecological baseline for investigating wilderness environments and identifying species habitat [5].

This study tried to identify the most likely vegetation indices or band ratio that best correlates with aboveground biomass/carbon in the *Damar* agroforest area. The significant correlation between these two parameters was found to have potential to facilitate carbon mapping in large *Damar* agroforest areas. The limitation of this study is that the carbon model was applied by using a pixel value only (digital information contained in satellite images). In fact, there are several factors that can affect the model such as spectral mixture, texture measure, etc. In the future, estimation and monitoring of carbon stocks can be estimated and predicted simply by analysing the satellite imagery without the necessity of conducting a large and expensive ground truth survey for all areas of *Damar* agroforest in Lampung, Indonesia and in other similar sites.

2. Methodology

2.1. Study Area

The study area focused in two villages in the *Krui* Sub-District of Gunung Kemala and Pahmungan, which formed an extended area of agroforest inland to the boundary of the Bukit Barisan Selatan National Park (BBSNP). Geographically, the agroforest area is located at 5°11′ S latitude, and 103°55′ E longitudes (Figure 1). The first *Damar* agroforest was established since the second half of 19th century. The Krui farmers started establishing *Damar* agroforest around the 1880s driven by the combination of decreasing abundance of naturally occurring trees and increasing resin demand for industrial vanish and paint industries [6]. Compared to other agricultural systems, *Damar* agroforest area is relatively equal to natural forest in terms of structure, function, dynamics and diversity [7]. The important characteristics of *Damar* agroforest system is that its establishment is a low-cost investment because the tree seedlings are often acquired from mature agroforest.

2.2. Biomass Measurements

A non-destructive method was used to estimate the biomass in tree and middle tree layers. Allometric equations relating to biomass developed earlier in the mixed secondary forest, Sumatra, Indonesia [8]. However, the value of the wood densities of all species was obtained from the website of the World Agroforestry *(http://db.worldagroforestry.org//wd)* and Plant Resources of South-East Asia (PROSEA). The equation is calculated as:

$$B\ (kg\ per\ tree) = 0.11\rho\ D^{2+c} \quad (1)$$

Where: ρ = wood density; D = DBH; c = constants (0.62).

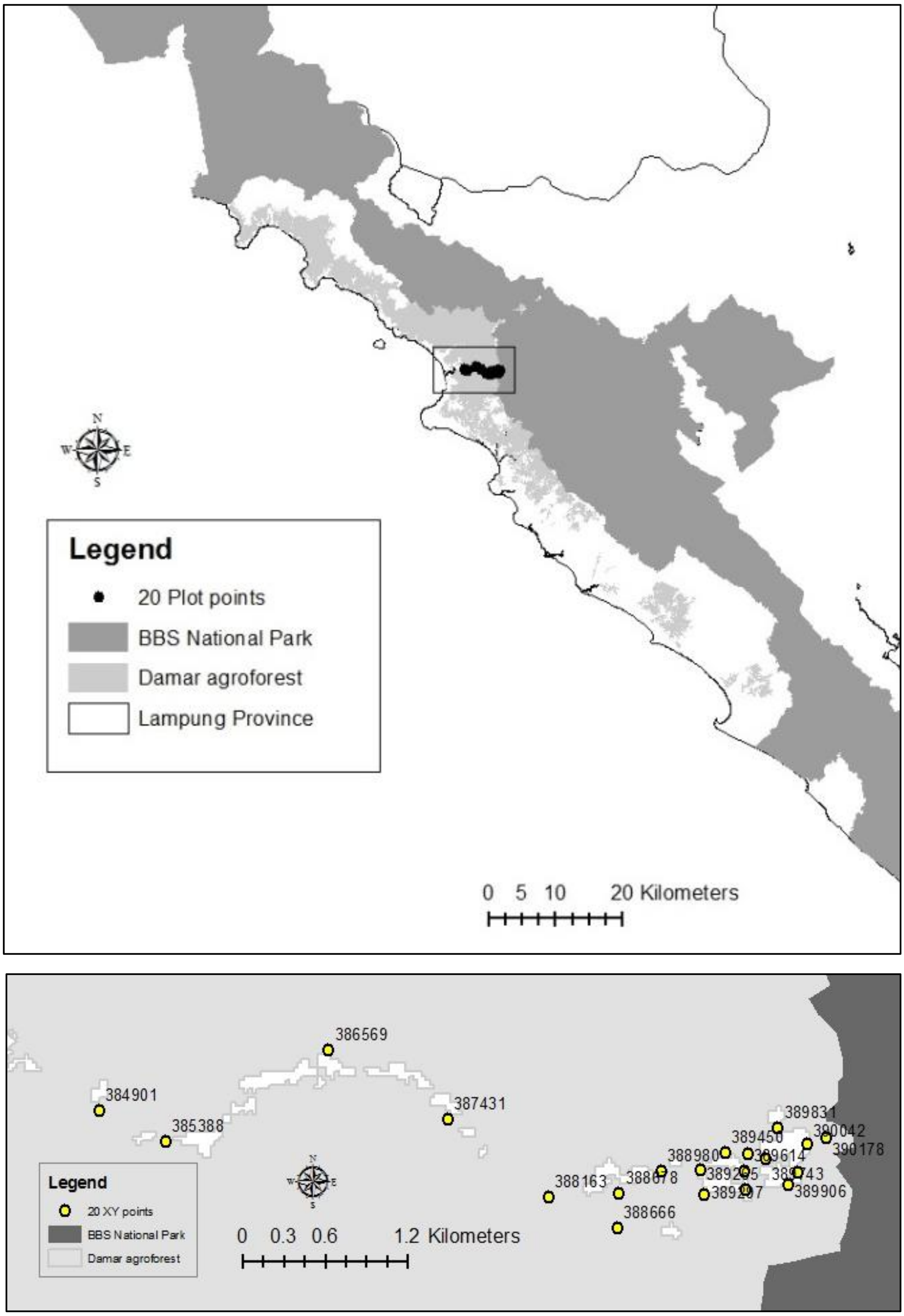

Figure 1. Location of Study.

Tree refers to large or mature log with DBH> 30 cm found on plot size 50 x 50 m; and middle tree refers to woody plants that are usually shorter with DBH of 5-30 m with plots size 5 x 5 m and herb-layer plots of 1 x 1 m size. Herb-layer biomass include all annual plants, regenerated sampling, and grass biomass. This layer is a part of the annual carbon cycle and it was estimated through harvesting [9] [10].

2.3. Plant Species Diversity
Species diversity was evaluated using species richness *(S)*, Shannon-Wiener's index *(H')*, and Simpson's predominance index *(D)* [11]. Species richness is the simple numerical count of the number of species found in a sampling unit [12]. Shannon's diversity index *(H')* is enhanced as the number of species increases and individuals are consistently distributed which is calculated as the proportion of species *i* relative to the total number of species *(pi)*, and then multiply by the natural logarithm of this proportion (ln*pi*). The resulting each species is summed up and multiply by -1 [12]. The Shannon-Wiener index equation is shown below [13]:

$$H' = -\sum_{i=1}^{s}\left(Pi\ \ln Pi\right) \quad (2)$$

Where: H' is the Shannon diversity index, *pi*= the proportion of individuals in the *i*-th species, s = numbers of species encountered,$\sum$ = sum from species i to species s.

The Simpson index provides to be useful at detecting shifts of dominance and also describes the stability and condition of some habitat [12]. If the index shows D = 1, one or some species is dominating the habitat. The equation of Simpson index is given below [12] [14] :

$$D = \sum Pi^2 \quad (3)$$

Where: D = Simpson index, p*i*= the proportion of individuals in the *i*-th species.
In order to calculate the index, the form appropriate to finite community is used:

$$D = \sum\left(\frac{ni(ni-1)}{N(N-1)}\right) \quad (4)$$

Where *ni*= the number of individuals in the *i*-th species and *N* = the total number of individuals. As *D* increases, the decrease of Simpson's index is usually expressed as 1 – *D* or 1/*D*.

2.4. Remote sensing bases assessment and mapping of biomass/carbon
The remote sensing data used to build the model is Landsat ETM+ 7 of band 1-5 and band 7. In addition, The Landsat ETM+7 images were downloaded in 11th of September 2011 and projection processing of the images was defined to WGS_1984_UTM_Zone_48S which is the standard projection system for Sumatra, Indonesia. Landsat data acquired from the USGS Global Visualization Viewer has been terrain-, radiometric- and geographically corrected. The value of each band and vegetation indices were calculated as the average of a 3 by 3 pixel window [15]. In addition, 10 vegetation indices were also used to investigate the significant correlation of the model. Previously, band ratios of 1-5 and 7 were processed with atmospheric correction methods that were converted from radian to reflectance. The atmospheric correction method is very important for physical measurement with remote sensing data. In addition, the reflectance calculated from Landsat ETM+7 data are using "Top of Atmosphere" (TOA) reflectance method.

$$R_\lambda = \frac{\pi * L_\lambda * d^2}{E_{sun,\lambda} * \sin(\theta_{SE})} \quad (5)$$

Where R_λ is the reflectance (unit less ratio), L_λ is the radiance, *d* is the earth-sun distance (in astronomical units), $E_{sun,}\lambda$, is the band-specific radiance-emitted by the sun, and θ_{SE} is the solar elevation angle [16]. This satellite imagery predicted the reflectance of objects at the TOA reflectance using the surface reflectance and atmospheric conditions information [17]. Recently, spectral indices have been applied for AGB assessment in different landscape and regions [18]. The single bands and indices were chosen because these had better performance for biophysical estimation in other tropical forests [2] [19]. The relationships between vegetation indices and biomass were also analysed to investigate the best model of biomass predicted by spatial analysis. The best fitting model of remote sensing was determined based on analysis of variance (ANOVA) that provides coefficient determination (R^2) [15]. In addition, validation of the model was analysed by the lowest value of the Root Mean Square Error (RMSE) [20] [21].

The goodness of fit statistics was calculated to identify the best fitting models that was given below:

A. Coefficient determination (R^2)

$$R^2 = 1 - \frac{RSS}{TSS} = 1 - \frac{\sum_{l-1}^{n}(Y_l - \hat{Y}_l)^2}{\sum_{i-1}^{n}(Y_i - \bar{Y})^2} \quad (6)$$

Note: RSS and TSS are residual sum and total sum of squares respectively.

B. Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}} \quad (7)$$

Note: Yi is the observed value of biomass; $\hat{Y}_i$ is estimated value of biomass by the models.

3. Results

3.1 Total aboveground biomass and basal area of Damar agroforest habitat

The total average of biomass was 416.96 tonnes/ha, indicating the carbon density was 208.48 tonnes C/ha. The aboveground biomass was divided into tree, middle tree, and herbaceous layers. In addition, biomass of tree layer was calculated to be 330.99 tonnes/ha; middle tree was 81.53 tonnes/ha; and herbaceous layer was 4.44 tonness/ha, or carbon densities of tree layer, middle tree layer, and herbaceous layer of 165.49 tonnes C/ha, 40.77 tonnes C/ha, and 2.22 tonness C/ha (50% of dry biomass) (Table 1) respectively.

The dry weight of tree stands based on 48 species (Table 2) was calculated to be 1,158,741.54 kg for *Shorea javanica*, 184,883.48 kg for *Lansium domesticum*, and 74,195.12 kg for *Durio zibethinus.* The middle tree's growing stage was found *Lansium domesticum* with the highest amount of dry weight of 830.53 kg, followed by *Areca catechu* at 553.20 kg; *Durio zibethinus* was 507.58 kg; and *Shorea javanica* was 506.82 kg. The total dry weight of the 42 species in middle tree stands was calculated to be 5944.93 kg (Appendix 4).

Tree stands having the diameter of more than 5 cm were calculated in twenty plots of 0.25 ha in the *Damar* agroforest for basal area estimation. Tree basal area is the cross-sectional area of a tree trunk measured at diameter at breast height (dbh) over the bark. It can be thought of as the surface area of a cut stump at a height of 1.3 m. There were as many as 73 species of trees and middle trees with more than 5 cm DBH, and the total number of trees was calculated to be 675 individuals. The result found that *Shorea javanica* has the highest number of species, with a density of 23.65 m^2/ha, followed by *Lansium domesticum* at 3.22 m^2/ha and *Durio zibethinus* at 1.82 m^2/ha. Stand basal area is the sum of the basal area of all living trees in an area; it is usually expressed in square metres per hectare (m^2/ha). However, stand basal area of *Damar* agroforest was calculated to be 35.12 m^2/ha (Appendix 5).

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Table 1. Aboveground biomass and carbon in the *Damar* agroforest (0.25 ha).

Plot	**Trees (tonnes/ha)**		**Middle Trees (tonnes/ha)**		**Herb (tonnes/ha)**		**Total (ton/ha)**	
	Biomass	Carbon	Biomass	Carbon	Biomass	Carbon	Biomass	Carbon
1	336.03	168.02	50.79	25.40	4.26	2.13	391.08	195.54
2	442.42	221.21	46.34	23.17	12.12	6.06	500.88	250.44
3	337.96	168.98	113.06	56.53	9.72	4.86	460.74	230.37
4	405.26	202.63	99.84	49.92	4.59	2.29	509.69	254.85
5	298.69	149.35	57.47	28.74	4.13	2.07	360.30	180.15
6	251.77	125.89	90.45	45.22	6.18	3.09	348.40	174.20
7	139.22	69.61	95.19	47.59	4.65	2.33	239.06	119.53
8	529.90	264.95	58.83	29.41	4.76	2.38	593.49	296.75
9	543.89	271.95	64.85	32.43	4.66	2.33	613.40	306.70
10	384.83	192.42	103.36	51.68	5.52	2.76	493.72	246.86
11	378.21	189.11	81.68	40.84	2.62	1.31	462.51	231.25
12	445.12	222.56	115.87	57.93	3.44	1.72	564.43	282.21
13	248.19	124.09	89.88	44.94	2.89	1.45	340.96	170.48
14	324.76	162.38	116.17	58.08	4.21	2.11	445.14	222.57
15	280.96	140.48	63.52	31.76	1.86	0.93	346.34	173.17
16	298.96	149.48	92.73	46.36	1.77	0.88	393.45	196.73
17	293.34	146.67	64.69	32.34	2.94	1.47	360.97	180.49
18	173.27	86.63	89.96	44.98	3.60	1.80	266.84	133.42
19	269.56	134.78	58.76	29.38	2.70	1.35	331.03	165.51
20	237.38	118.69	77.23	38.62	2.23	1.11	316.84	158.42
Total	6619.72	3309.86	1630.69	815.34	88.86	44.43	8339.27	4169.63
Average	330.99	165.49	81.53	40.77	4.44	2.22	416.96	208.48

Table 2. Dry weight of tree based on species and vegetation growth stage (DBH > 30 cm).

No.	Tree's Species	Biomass (kg)	No.	Tree's Species	Biomass (kg)
1	*Shorea javanica*	1158741.54	25	*Myristicacelebica*	2841.15
2	*Lansiumdomesticum*	184883.48	26	*Artocarpusheterophyllus*	2716.89
3	*Duriozibethinus*	74195.12	27	*Eugenia polyantha*	2684.89
4	*Arengapinnata*	31261.97	28	*Derris elliptica*	2681.09
5	*Lithocarpusspicatus*	22145.68	29	*Tetramelesnudiflora*	2410.77
6	*Ficuseelastica*	20673.77	30	*Aleuritesmoluccana*	2196.78
7	*Spondiaspinnata*	18846.68	31	*Mangiferacaesia*	1764.51
8	*Parkiaspeciosa*	16335.02	32	*Pithecellubiumcypearia*	1632.80
9	*Eugenia polycephala*	15419.27	33	*Caralliabrachiata*	1591.04
10	*Gnetumgnemon*	14292.34	34	*Macaranga diepenhorstii*	1476.65
11	*Pterospermumjavanicum*	12178.64	35	*Ficusvariegata*	1139.81
12	*Terminalia catappa*	12043.51	36	*Cocos nucifera*	1124.08
13	*Nepheliumlappaceum*	9570.92	37	*Penoremacanescens*	1123.92
14	*Parastemonurophyllum*	8581.55	38	*Diospyros cauliflora*	1075.91
15	*Dehaasiaincrassata*	8392.67	39	*Artocarpus integer*	984.95
16	*Kompassiaexcelsa*	6688.10	40	*Erythrina variegata*	980.29
17	*Quercus sumatrana*	4708.02	41	*Alstoniascholaris*	961.95
18	*Ficusdeltoidea*	4537.71	42	*Eugenia malaccensis*	758.44
19	*Bischofiajavanica*	3687.88	43	*Pometiapinnata*	715.31
20	*Bambusa sp.*	3642.14	44	*Ficusbenjamina*	563.58
21	*Ficusracemosa*	3588.98	45	*Archidendronjiringa*	561.81
22	*Homalathuspopulneus*	3497.08	46	*Palaquiumrostratum*	537.17
23	*Pithecellobiumjiringa*	3226.90	47	*Alstoniaangustiloba*	462.05
24	*Syzigiumgrandis*	2954.58	48	*Toonasureni*	391.77
Total Biomass (kg)					1677471.17

3.2. Biodiversity of complex agroforestry-based Dipterocarp forest

3.2.1. The distribution of DBH and species composition in Damar agroforest. A total of 20 stratified sample plots, each covering an area of 2500 m^2, were used in this study. *Shorea javanica* of *Dipterocapaceae* family was found to be the dominant species with a total of 51% of all the species found, followed by *Lansium domesticum* of *Maliaceae* (11%), *Durio zibethinus* of *Malvaceae* (6%), and *Parkia speciosa* of *Leguminoceae*(5%) (Figure 2). In total, field inventory of trees and middle trees identified 73 species belonging to 35 families and 15 species of herbaceous layer belonging to 12 families. The function of an agroforest is not only to produce damar resin but it also produces other kinds of products from other trees such as timber, fruit or food, medicine plant, colouring matter, etc. The benefits of all species was obtained from Plant Resources of South-East Asia (PROSEA).

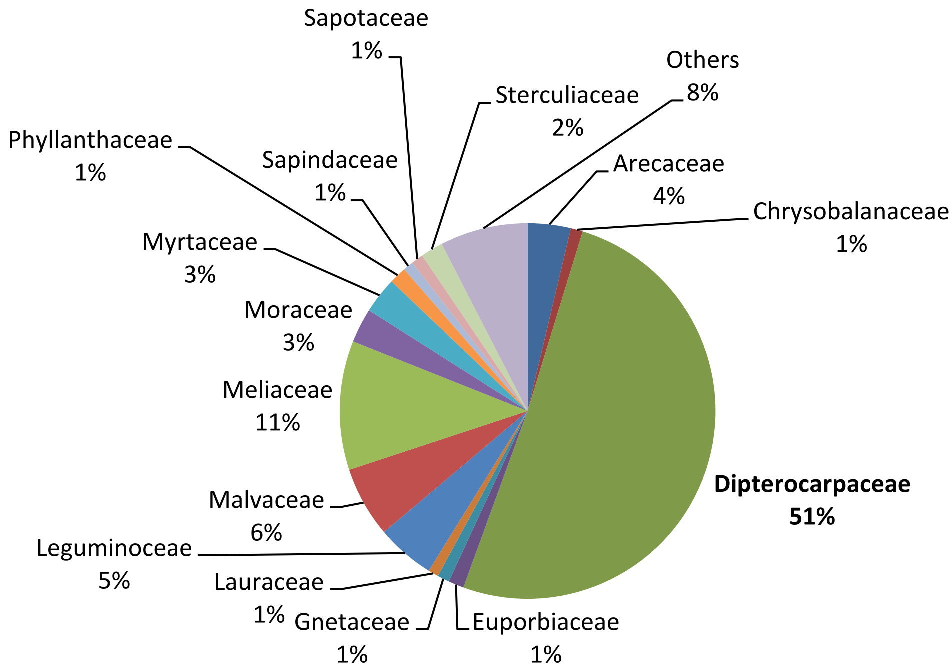

Figure 2. Distribution of family of tree species in the *Damar* agroforest.

A total of 675 trees and middle trees were measured in the sample plots. The majority of the tree's diameter was clasified having dbh of range between 35-40 cm covering a total of 11.41%. While, the 20-25 cm and 25-30 cm dbh ranges were the lowest diameter distribution of trees in the sample plots only found to be 0.3% (Figure 3). This agroforest was the final stage of agroforestry and predicted comprised of more than 20 years old *Damar* agroforest. Nevertheless, dbh of more than 80 cm was found among the 6.81% of the population. This range was dominated by *Shorea javanica* and fruit trees such as *Durio zibethinus* and *Lansium domesticum*. However, the 5-10 dbh range which covered 7.26% in this area were due to replacement planting by the Krui farmers. Damar trees can remain productive for 50-80 years.

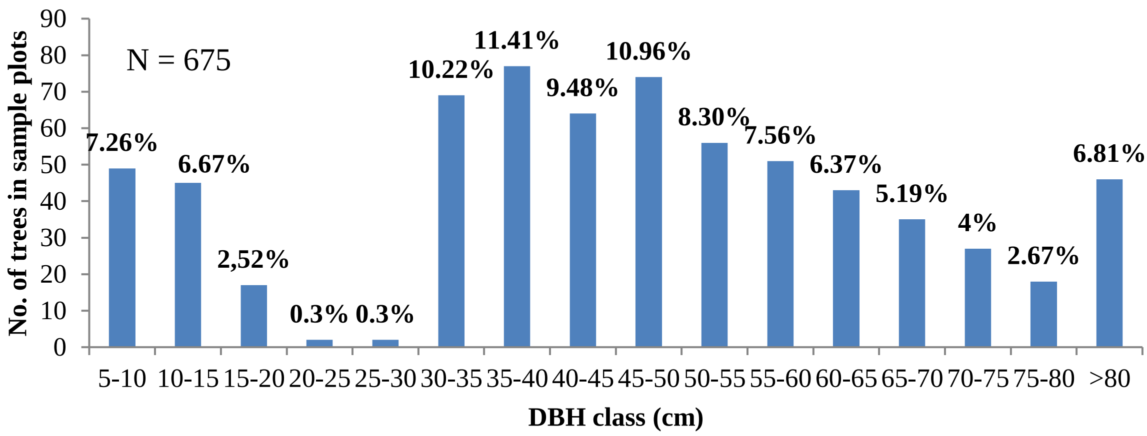

Figure 3. Distributions of diameter of trees with more than 5 cm DBH in the sample plots.

3.2.2. Plant species diversities based on habitat level of Damar agroforest. *Damar* agroforest was grown as natural forest in the southern part of Lampung Province. The agroforest was found in several villages in Krui Sub-District. This study focused on two villages, *i.e*., Pahmungan and Gunung Kemala, with a long history of *Damar* agroforest and also buffers a national park.

In Pahmungan village, as many as 38 species of tree and 25 species of middle tree were found. The Shannon-Wiener index was calculated at 1.69 for tree layer and 2.99 for middle tree layer, while the Simpson index was recorded at 0.63 for tree layer and 0.96 for middle tree layer (Appendix 6). Whereas in Gunung Kemala Village, as many as 28 species of tree and 28 species of middle tree were recorded. The Shannon-Wiener index was calculated at 1.97 for the tree layer and 3.06 for the middle tree layer, while the Simpson index was recorded at 0.58 for tree layer and 0.95 for middle tree layer (Appendix 7).

Plant species diversity was measured for species with *DBH* of more than 5 cm of tree species. The species richness was recorded at 73 species along with 15 species of herbaceous plant. However, the Shannon-Wiener index (H') was calculated at 2.36 which classified as moderate. In addition, the Simpson index (D) was 0.73 (Appendix 8).

3.3. The relationship between biomass and vegetation indices/ band ratios

The spectral band values were extracted from window pixel and they were validated by atmospheric correction of Landsat 7 ETM+ imaginary of 11 September 2011. The statistical analysis provided on the regression models based on aboveground biomass as dependent variable, and the vegetation indices and spectral band of the Landsat 7 ETM+ as independent variable. Multiple linear regression models were fitted to the scatter plot of aboveground biomass per plot versus vegetation indices/band ratios. These analyses provided to find the best significant model using coefficient determination (R^2) of ANOVA, and the validation model was determined using RMSE with the lowest value. The relation between band ratios and carbon is shown in scatter plots (Appendix 1).

The model estimator based on spectral reflectance of Landsat 7 ETM+ is provided in Table 18. The result found a significant correlation of band 7 (R^2 = 0.44; F-stat. = 14.88 > F crit. = 4.38, p-value = 0.001, df = 1, 19), followed by band 2 (R^2 = 0.40; F-stat = 12.78 > F crit. = 4.38, p-value = 0.002, df = 1, 19), band 3 (R^2 = 0.40; F-stat. = 12.59 > F crit. = 4.38, p-value = 0.002, df = 1, 19) and band 5 (R^2= 0.37; F-stat. = 11 > F crit. = 4.38, p-value = 0.004, df = 1, 19). However, band 1 (R^2 = 0.30; F-stat. = 7.977 > F crit. = 4.38, p-value = 0.011, df = 1, 19) and band 4 (R^2 = 0.32, F-stat. = 8.93 > F crit. = 4.38, p-value = 0.008, df = 1, 19). Bands 1 and 4 were also significant but lower than bands 7, 2, 3 and 5. Therefore, the fourth band reflectance (bands 7, 2, 3, and 5) was used as the input with vegetation indices to determine the best model. This model was also validated using RMSE for band 7 (RMSE = 52.82), followed by band 3 (RMSE = 54.70), band 2 (RMSE = 54.53), band 5 (RMSE = 56.13), band 1 (RMSE = 59.19), and band 4 (RMSE = 58.17) (Appendix 9).

Based on statistical analysis, it was found that the single reflectance band 7 was the best model due to means significant of 1%, relatively (R^2 = 0.44; F-stat. = 14.84 > F crit. = 4.38, p-value = 0.001, df = 1, 19); and it was also validated on the lowest RMSE value as 52.85. Even though the model based on reflectance band 7 was quite good to predict biomass and carbon, but it required to examine the model from vegetation indices and the combination between band ratios and vegetation indices.

All of vegetation indices were each validated using the same methods. There were only five vegetation indices that were significant with a p-value < 0.05. The indices were Greenness (R^2 = 0.39, p-value = 0.02), TNDVI (R^2 = 0.38, p-value = 0.003), Simple Ratio 4/3 (R^2 = 0.27, p-value = 0.01), SAVI (R^2 = 0.38, p-value = 0.003) and NDVI (R^2= 0.36, p-value = 0.004). This was followed by data validation of the lowest RMSE to develop the model. However, the lowest RMSE was found in Greenness with RMSE = 54.89, followed by SAVI with RMSE = 55.54, TNDVI with RMSE = 55.68, and NDVI with RMSE = 56.29 and Simple Ratio 4/3 with RMSE = 60.21 (Appendix 10).

The following step involved the combination of 4 spectral bands (band 2, 3, 5, and 7) and 5 vegetation indices (Greenness, TNDVI, SR43, SAVI and NDVI) to become the model. However, the result showed to be insignificant with R^2 = 0.66, p-value = 0.09 and RMSE = 54.39, thus it was still necessary to find the significant model by using stepwise multiple linear regressions. The first step results found that band

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2, band 3, band 7, TNDVI and SAVI had the significant correlation of $R^2 = 0.57$, p-value = 0.008, and RMSE = 49.08. Based on the analysis, variables were omitted one by one, to determine the higher significance. The second found that band 3, band 7, TNDVI, and SAVI had $R^2 = 0.57$, p-value = 0.007, and RMSE = 50.41, and the third step found band 7, SAVI, and TNDVI to have $R^2 = 0.55$, p-value = 0.003, and RMSE = 50.14 (Appendix 11).

Finally, single, multiple and stepwise regression was tested by ANOVA and RMSE. Therefore, the best model for carbon sequestration was related to reflectance band 7. The significant linear relation for carbon sequestration of *Damar* agroforest based on reflectance band 7 was Y *= 267.83 – 1625.5 band7* ($R^2 = 0.44$; F-stat. = 14.84 > F crit. = 4.38, p-value = 0.001, df = 1, 19) and RMSE = 52.84, where Y is the biomass as the dependent variable in tonnes/ha with significant p-value of < 0.001.

The carbon distribution map was produced by using the reflectance band 7. This model can facilitate carbon mapping by using *Raster Calculator* in ArcGIS 10. Carbon map was also used to predict the total carbon in a large area of *Damar* agroforest. In the future, carbon content can be simply predicted by using this model without massive and expensive field survey for *Damar* agroforest or similar site.

The relationship between carbon and vegetation indices can be predicted by showing scatter plot of Pearson correlation (Appendix 2). However, the distribution of the aboveground carbon (tonnes C/ha) in *Damar* agroforest was also shown in Appendix 3. Calculation of the total carbon in the large area of *Damar* agroforest was shown in Table 3.

Table 3. Carbon value based on class by using spatial estimation.

Classes	Carbon Value	Mean of Carbon Value	Pixel Size	Pixel Value	Raster Value (ha)	Total Carbon (tons C)	Carbon (%)
1	0-50	25	0.09	34407	3096.63	77,415.75	7
2	50-100	75	0.09	49766	4478.94	335,920.50	10
3	100-150	125	0.09	241564	21740.76	2,717,595.00	49
4	150-200	175	0.09	157110	14139.9	2,474,482.50	32
5	> 200	225	0.09	6132	551.88	124,173.00	1
Total					44008.11	5,729,586.750	100
Average of Carbon (ton C/ha)						130.1938836	

The carbon density of *Damar* agroforest area was calculated with a mean value of 130.19 tonness C/ha with the total carbon potential of 5,729,586.75 tonness C. However, the total size of *Damar* agroforest area was calculated to be 44,008.11 ha which was bordering the southern part of the national park. In addition, the highest amount of carbon was found within the 100-150 tonness/ha class, which was approximately 21740.76 ha (50%) of the area. This was followed by the 150-200 tonnes/ha class with 14139.9 ha (32%); the 50-100 tonnes/ha class with 4478.98 ha (10%); the 0-50 tonnes/ha class with 3096.63 ha (7%); and the > 200 tonnes/ha class with 551.88 ha (1%) (Figure 4).

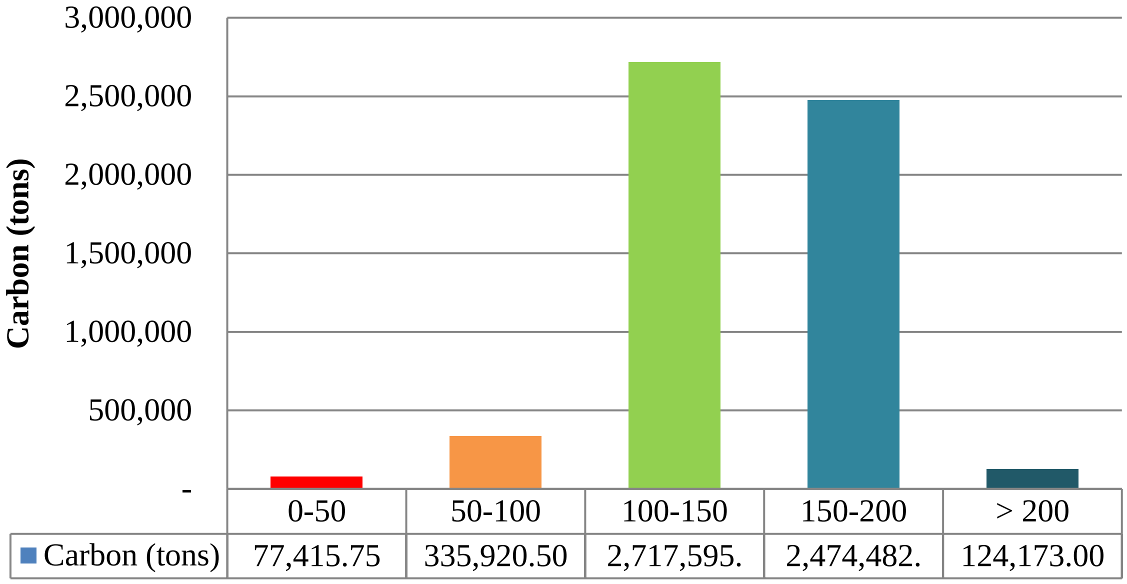

Figure 4. Carbon class (tons C/class) in the *Damar* agroforest area.

The map showing the highest biomass density areas were mostly in the upper parts of the *Damar* agroforest that are near BBSNP. In addition, this area was included in the *KDTI* area. This agroforest still has relatively good vegetation cover that was indicated by the high value of aboveground biomass. Generally, the agroforest consisted of the bigger diameter trees such as *Shorea javanica, Lansium domesticum, Durio zibethinus, Parkia speciosa, Arenga pinnata, Eugenia plycephala,* and *Perospermum javanicum.* The distribution of trees was calculated to be higher for DBH > 80 cm at 6.81%; and in the middle phase with DBH of 30-35 cm to 60-65 cm at 6.37% and 11.71% respectively.

4. Discussions

Damar agroforest was observed based on 20 sample plots. Fifty-one percent of the species were dominated by *Shorea javanica* belong to *Dipterocpaceae* family. Therefore, this area was called *"Repong Damar"* or *Damar* agroforest. The *Damar* agroforest are ontinually protecting and buffering the national park effectively. Compared to the other tree-based agricultural systems, *Damar* agroforests are relatively equal to natural forest in terms of structure, function, dynamic and diversity [22].

This complex agroforestry was identified to be the final stage of *Damar* agroforest [7]. In addition, this study found the higher number of diameter > 80 cm at 6.81%. However, 7.26%, 6.67% and 2.52% were found in the first phase for DBH of 0-5 cm, 5-10 cm, and 10-15 cm respectively. One indicator of the final phase was that the farmers still tapped the resin regularly and harvested fruit trees. Farmers replaced one by one old damar tree and other fruit trees using both natural regeneration and enrichment planting. In addition, old agroforests may vanish while new *Damar* agroforest would be established. In addition, the highest percentage was found to be at DBH 35-40 cm at 11.41%.

The last stage of *Damar* agroforest has a natural permanent tree cover and high stature which was the same as natural forest. Furthermore, canopy can reach more than 40 metres with a multi-strata structure and a high diversity of forest plants and animals.

Government and conservation NGOs are particularly interested in maintaining the *Damar* agroforest because of its visible function as a natural buffer to the BBSNP. The southern part of the national park was still covered by natural forest which was bordered by the *Damar* agroforest. Although the national park had lost about 19% of its forest cover between 1972 and 2002, mainly due to agricultural encroachment, nevertheless the total *Damar* agroforest has increased about 1% slightly in 1997 to 2002 [23] [24]. This agroforest still effectively functioning as a buffer for the national park even though it cannot protect the entire natural forest. Moreover, it is still important to protect this agroforest since it was useful in maintaining farmers' livelihoods and also protecting the natural forest.

This study has estimated the aboveground biomass to be 416.96 tonnes/ha; it signifying the total aboveground carbon potential was 208.48 tonnes C/ha. However, *Dipterocarp* forest spreads in many countries across South-East Asia such as Malaysia, Philippine, and Thailand (Table 1). Analyse the stand biomass from 172 tonnes/ha to 506 tonnes/ha for distributed and undistributed forests of *Dipterocarp* in Sabah, Malaysia [25]. However, [26] also estimate a total of 167.9 Mg C/ha of aboveground carbon in the Tropical Lowland Dipterocarp Rainforest of Sabah, Malaysia. In addition, the carbon storage in the Dry *Dipterocarp* Forest in Thailand based on the slope range of 20-40% was 43.22 tonnes C/ha and the range of < 20% was 14.55 tonnes C/ha, while for Mixed Deciduous Forest on slope range < 20% was 27.94 tonnes C/ha, respectively [27]. In the Philippine, [28] calculated a total of 258 Mg C/ha of Unlogged Forest. In addition, 98% of the aboveground biomass C was found in trees with DBH ≥ 19.5 cm and 34% of soil organic carbon. After logging, the carbon stock declined to 50%. However, this study found that 79% of carbon within tree (DBH > 30 cm); 20% of carbon within the middle (5-30 cm of DBH); and 1 % within herbaceous layer (DBH < 5 cm). Furthermore, the carbon density in Sumatra Lowland and Hilly *Dipterocarp* Forest was found to be 135-240 Mg C/ha, with a mean of carbon density of 180 Mg C/ha [29].

The natural forest on the peatland forest consisted of 600 tonnes C/ha of of biomass , with carbon content of 340 tonnes/ha in Central Kalimantan, Indonesia [30]. In addition, natural forest and shade and sun coffee were recorded to contain 262.82 and 52 Mg C/ha in Sumatra, Indonesia [31]. In the same island but different forest type, [32] found the aboveground biomass of *Bruguiera parviflora* community to be 42.94 tonnes/ha to 89.68 tonnes/ha; *B. sexangula* from 75.99 tonnes/ha to 279.03 tonnes/ha; and *Rhizophora apiculata* was 40.70 tonnes/ha.

The basal area of *Damar* agroforest was calculated to be 35.12 m^2/ha in the 20 plots of 0.25 ha with DBH > 5cm. This study was conducted in Pahmungan and Gunung Kemala Villages and was held in 2011. However, [33] estimated one hectare plot in each three sites of *Damar* agroforest, *i.e*., in Gunung Kemala, Pahmungan, and Penengahan, and found the basal area in 1993, to be 41.94 m^2/ha in Gunung Kemala; 25.3 m^2/ha in Pahmungan; and 25.9 m^2/ha in Penengahan. Based on this study, basal area was conducted in 1993 and 2011. The Vincent study showed relatively no significant difference in value with this study. It indicated that damar agroforest condition was relatively sustained from 1993 to 2011. However, [2] estimated the *KDTI* area has decreased about 4% from 1997 to 2002. Moreover it slightly increased about 1% of excluded and included of *KDTI area* from 1997 to 2002. Therefore, *Damar* agroforest relatively sustains in buffering national park and it is effectively supporting ecosystem services and the farmers' livelihoods.

Damar agroforest is a type of complex agroforestry, which is naturally the same as forest in terms of appearance and function. The agroforest system involves a high number of components (such as trees, middle trees/seedling, lianas and herbs). Their appearance and functions were close to those observed in natural ecosystems, either primary or secondary forest.

Biodiversity encompassed a range of different levels of organisation from genetic variation between individuals and populations, to species diversity, assemblages, habitat, landscapes and bio geographical provinces [34]. Species richness of the agroforest was 73 tress species belonging to 35 families; in addition to the 15 herbaceous plants belonging to 12 families. Moreover, the Shannon - Wiener index was found to be moderate with a value of 2.37. The value of Shannon - Wiener index relates to species richness but it is also influenced by the underlying species abundance distribution. [35] calculated the Shannon-Wiener index to be 2.006 in *Dipterocarp* forest in Kalimantan; followed by 5th years logged over area of *Dipterocarp* to be 2.066; 10th years logged area to be 1.894; 30th years logged over area to be 1.998. The average Shannon-Wiener index in these areas were calculated at 1.998 in moderate level diversity. Comparing the reesult to this study, it can be concluded that *Damar* agroforest is better in term of habitat stability and species abundance distribution.

The Simpson Index is useful in detecting shifts of dominance [12]. If D =1, the habitat was dominated by one or more species. Based on the category, the Simpson Index for the *Damar* agroforest was found to be 0.73. Thus 70 % of *Damar* agroforest areas might be dominated by one or more species. Based on species distribution, the dominant species was *Shorea javanica* belong to *Dipterocarpaceae* (51%), *Lansium domesticum* belong to *Maliaceae* (11%), and *Durio zibethinus* belong to *Malvaceae* (6%). Although the species was dominated by fruit species, the *Damar* agroforest was still in stable condition and showed normal species distribution. This result suggested that *Damar* agroforest was better than logged over area in terms of sustainability of biodiversity. Whereas, the hills and lowlands areas of Kalimantan and Eastern Sumatra, which comprised the last tracts of mixed *Dipterocarp* forest are being exploited for timber and rapidly converted [36].

The spectral reflectance band 7 was the best significant model with a p-value < 0.001. The model was compared with another spectral band and vegetation indices using simple and multiple regression. This indicated the single spectral reflectance band in medium resolution images such Landsat-7 ETM+ was feasible to predict aboveground biomass/carbon in *Damar* agroforest. The decomposition is not essential to obtain the proportion of vegetation within the mix component with vegetation indices in this area. Several studies [18] [25] [37] found that a single spectral band ratio or NIR signature was feasible to predict the aboveground biomass.

The use of all band ratios (1 to 5, and 7) of the Landsat-7 ETM+ produced a lower R^2 value of the regression model compared to band 7 (R^2 = 0.44, p-value = 0.001). However, combination of band 7, TNDVI and SAVI could improve the coefficient determination (R^2 = 0.55, p-value = 0.003) but the significance of the p-value was still lower than that of band 7. In *Damar* agroforest area, these indices combination were not used to predict the aboveground biomass. Therefore, the spectral band 7 was chosen as the best model to predict the aboveground biomass or carbon within this site.

Several methods based on spectral reflectance or vegetation indices have been developed and tested. However, forest inventory data were integrated with six reflectance TM bands and ten vegetation indices to estimate aboveground carbon. [38] conclude that band TM 5 and linear transform indices were strongly correlated with the aboveground biomass. However, [39] found that all Landsat ETM bands and TNDVI were significantly correlated to crown cover percentage, and the best model for predicting crown cover included band 1 and 7, and TNDVI as the predictors. The model is expected to be easier in predicting biomass, slope, volume, and basal area. Modified Soil Adjusted Vegetation Index (MSAVI) and near infrared reflectance were also useful to retrieve biophysical parameter [40]. [40] examined that MSAVI and infrared reflectance strongly correlated with the aboveground biomass for pine forest.

However, for lowland and mixed *Dipterocarp* forest, the use of remote sensing-based methods to estimate aboveground biomass or forest stand parameters was highly varied in their results. [18] obtain a relatively good coefficient determination (R^2= 0. 69) when neural network was applied to predict aboveground biomass. In addition, [25] report that the average radiance in band 4 of Landsat TM 5 was highly correlated with aboveground biomass (R^2= 0.76) in the Ulu Segama Forest Reserve in Sabah, Malaysia, part of Borneo Island. However, the model was not validated, implying that the model applicability for other areas was unreliable. Consequently, another method was required to fill in this knowledge gap.

The regression model of [37] found a strong coefficient determination (R^2 = 0.722) between aboveground biomass and band 5, and can predict a maximum dry weight of aboveground carbon to be 150 tonness/ha. In this study, the average aboveground carbon based on carbon map was estimated to be 130.19 tonness/ha and field survey estimated the aboveground biomass to be 416.96 tonness/ha (or 208.48 tonness/ha of aboveground carbon) in *Damar* agroforest based complex agroforestry system. [25] conducted their research in the natural *Dipterocarp* forest, nearly to our study area, but the maximum of aboveground biomass in their forest was 500 tonnes/ha.

One of the limitations in estimating aboveground biomass/carbon using vegetation indices is a signal recorded by a sensor in one pixel, in fact a spectral mixture of radiance or reflectance of all components of the earth's surface covered by that pixel. Related to vegetation analysis, spectral mixture analysis is commonly applied to study vegetation abundance outside the tropical forest [41]. However, texture measures are relatively less important than spectral signature in some areas with slow vegetation growth [42]. In addition, [41] applied spectral mixture analysis in selectively logged tropical forest to improve the estimation accuracy of aboveground biomass in *Dipterocarp* forest. Her study also found that with

Landsat ETM+7; band 4 has the highest correlation, followed by band 5 and band 7. Therefore, these bands together can also used to generate linear regressions to predict the aboveground biomass.

In this research, the most feasible model was found in three categories: First, for the single reflectance band, band 7 was the best estimator for aboveground biomass and carbon; second, the vegetation indices at Greenness as a feasible model to predict aboveground biomass and carbon, and; third, the combinations between band ratios and vegetation indices by using stepwise regression analysis found that band 7, TNDVI, and SAVI as the alternative predictors for aboveground biomass and carbon. Therefore, band 7 was chosen as the ideal model to predict carbon content based on spatial method for *Damar* agroforest and other similar sites. The model based on simple linear regression produced the value of $R^2 = 0.44$; F-stat. = 14.88 > F crit. = 4.38, p-value = 0.001, df = 1, 19; and the model has the lowest value of RMSE = 52.84. This model was chosen as the ideal model to predict carbon content in *Damar* agroforest with an equation of Y = 267.83 – 1625.5 band 7 and it was feasible to map carbon content.

Based on [43], the spectral reflectance of band 7 (2.08 – 2.35 μm, mid-infrared) is also used for vegetation moisture although generally band 5 is preferred for that application, as well as for soil, discrimination of rock types, hydroxyl ion absorption, and hydrothermal or geology mapping.

The relation derived for carbon sequestration needs to be verified by measuring sample trees in permanent plots. Further research is required to develop an equation from the annual wood increment from species specific relations. It also needs further research to establish better relationships among biomass, plant species diversity and vegetation indices/band ratios. Additional data on forest type, canopy cover, and height could be integrated to obtain better predictive model based on spectral data.

5. Conclusion

The Damar agroforest is an important site in terms of protecting natural forests and carbon sequestration with high biodiversity, stable community and preferable site for carbon trading mechanism. Based on the statistical analysis, the model was appropriate to facilitate carbon mapping in large *Damar* agroforest areas of 44,008.11 ha; with the average carbon content of the large *Damar* agroforest to be 130.19 tonnes C/ha, where such carbon content is nearly equal to that of natural *Dipterocarp* forest (49% ~ 84%). Therefore, estimation and monitoring of carbon contents could be estimated and predicted simply by analysing the satellite imagery without the necessity of conducting a large and expensive ground truthing survey for all areas of the *Damar* agroforest in Lampung, Indonesia and in other similar sites.

Acknowledgement

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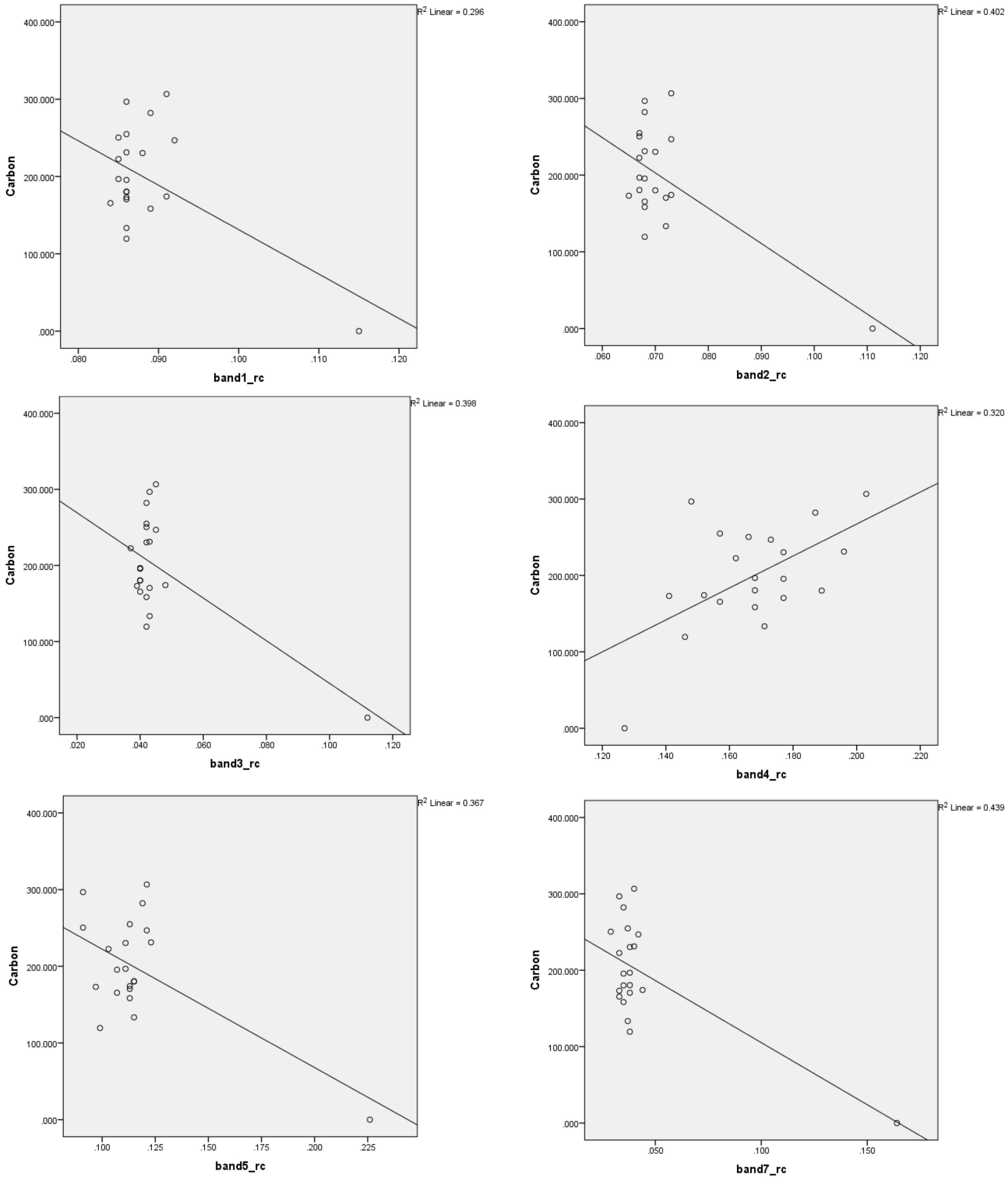
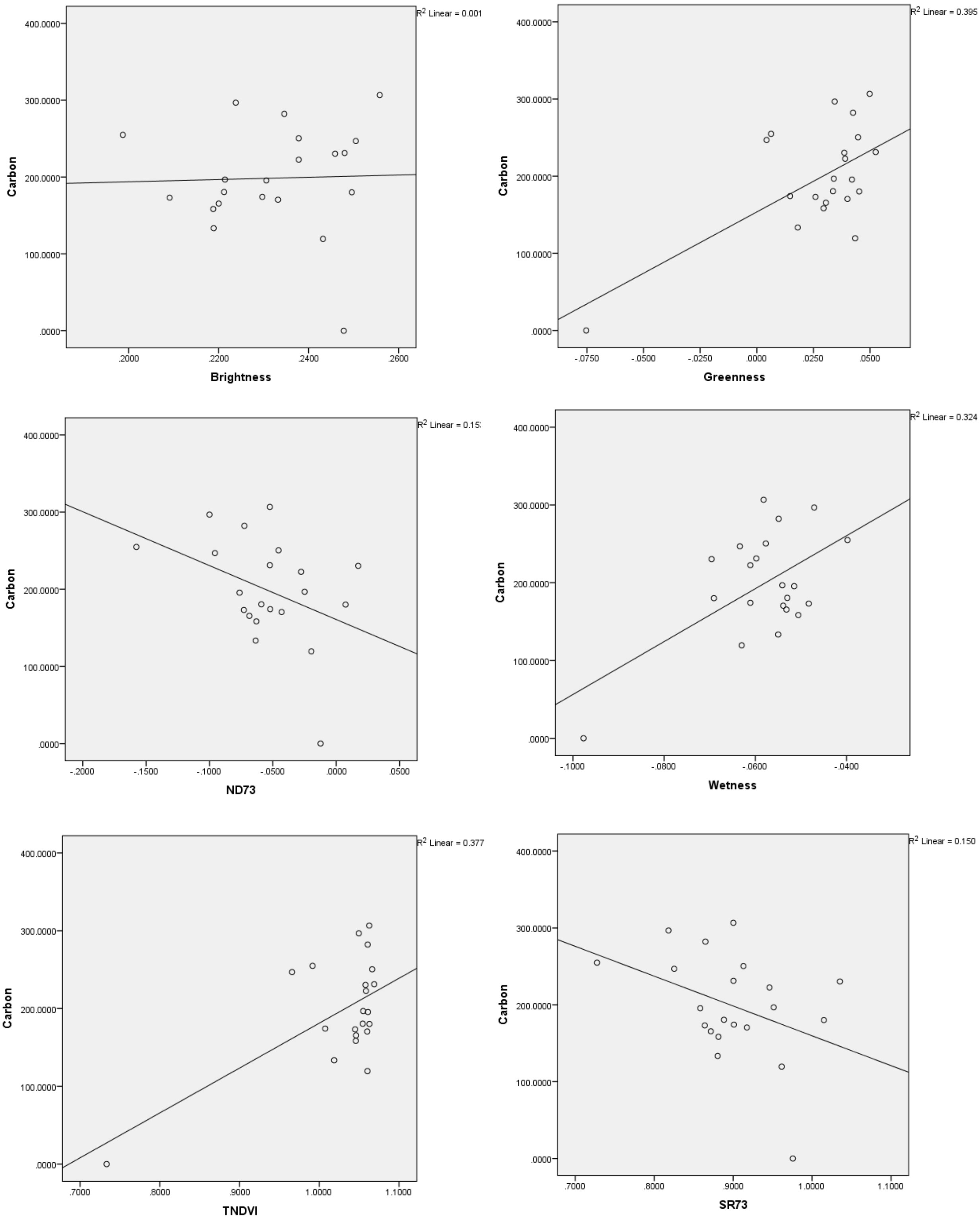
Appendix



Appendix 1. Scatter plots of biomass against band ratios of 1-5 and 7.



Appendix 2. Scatter plots of biomass against vegetation indices of Brightness, Greenness, ND73, Wetness, TNDVI, and SR73.

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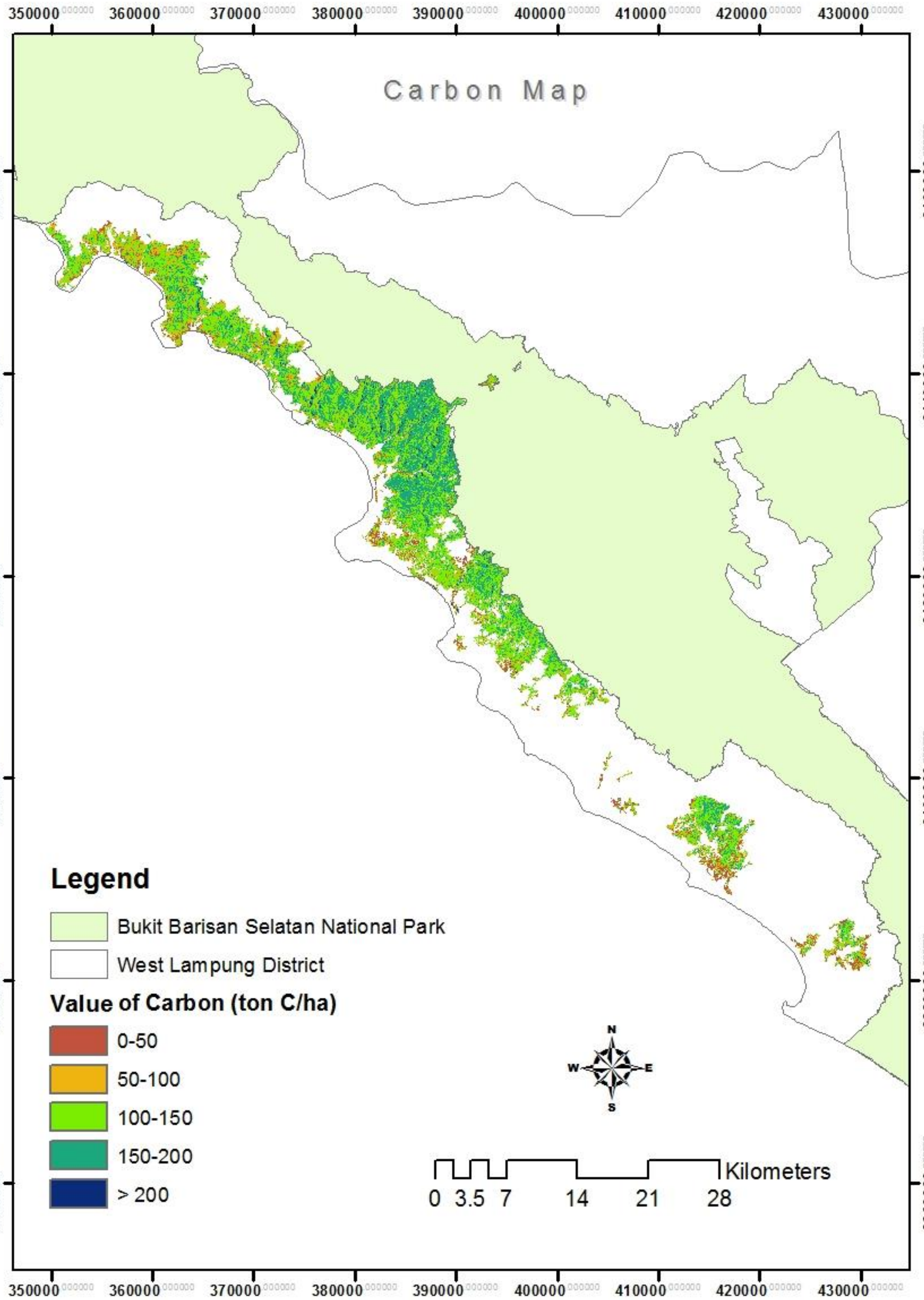

Appendix 3. Distribution of aboveground carbon (ton C/ha) in *Damar* agroforest, Lampung, Indonesia.

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Appendix 4. Dry weight of middle trees stand based on species and vegetation growth stage (5-30 cm DBH).

No.	**Middle tree's Species**	**Biomass (kg)**	**No.**	**Middle tree's Species**	**Biomass (kg)**
1	*Lansiumdomesticum*	830.53	22	*Dendrocnidecfstimularis*	66.42
2	*Areca catechu*	553.20	23	*Nepheliumlappaceum*	60.52
3	*Duriozibethinus*	507.58	24	*Parkiaspeciosa*	60.32
4	*Shorea javanica*	506.82	25	*Pterospermumjavanicum*	53.11
5	*Penoremacanescens*	479.62	26	*SchimawaliciiKorth.*	52.91
6	*Parastemonurophyllum*	265.22	27	*Gossypium sp.*	49.34
7	*Mimusopselengi*	224.99	28	*Mischocarpuspentapetalus*	49.34
8	*Fiscus variegata*	224.06	29	*Vitex avinata*	43.73
9	*Bischofiajavanica*	207.84	30	*Elateriospermumtapos*	35.45
10	*Gliricidiasepium*	193.87	31	*Payenaacuminata*	33.73
11	*Antidesmabunius*	190.81	32	*Albiziasaman*	28.48
12	*Pithecellobiumjiringa*	147.73	33	*Mangiferacaesia*	28.48
13	*Baccaureadulcis*	144.13	34	*Ficusseptica*	21.61
14	*Eugenia polycephala*	141.50	35	*Syzygiumaromaticum*	21.61
15	*Clausenaexcavata*	114.38	36	*Ficusampelas*	19.58
16	*Ficuseelastica*	108.60	37	*Averrhoacarambala*	15.87
17	*Eugenia malaccensis*	92.35	38	*Syzigiumgrandis*	15.87
18	*Anthocephaluscadamba*	88.36	39	*Dilleniaindica*	12.64
19	*Celtissumatrana*	87.68	40	*Diospyros cauliflora*	12.64
20	*Ficusquercifolia*	73.15	41	*Caryota sp.*	8.61
21	*Piper baccatum*	66.73	42	*Coffeacanephora*	5.49
Total Biomass (kg)					5944.93

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Appendix 5. Number of trees with DBH of 5 cm and its basal area within Damar agroforest (m2/ha).

No.	**Species**	**Trees**	**Basal Area**	**No.**	**Species**	**Trees**	**Basal Area**
1	*Shorea javanica*	342	23.649	38	*Elateriospermumtapos*	2	0.002
2	*Lansiumdomesticum*	74	3.218	39	*Eugenia malaccensis*	2	0.028
3	*Duriozibethinus*	40	1.825	40	*Eugenia polyantha*	2	0.071
4	*Parkiaspeciosa*	16	0.577	41	*Lithocarpusspicatus*	2	0.274
5	*Arengapinnata*	15	0.679	42	*Mangiferacaesia*	2	0.053
6	*Eugenia polycephala*	13	0.396	43	*Myristicacelebica*	2	0.085
7	*Pterospermumjavanicum*	13	0.375	44	*Pithecellubiumcypearia*	2	0.061
8	*Areca catechu*	8	0.027	45	*Tetramelesnudiflora*	2	0.107
9	*Parastemonurophyllum*	8	0.142	46	*Vitex avinata*	2	0.003
10	*Pithecellobiumjiringa*	8	0.131	47	*Albiziasaman*	1	0.002
11	*Bischofiajavanica*	7	0.099	48	*Aleuritesmoluccana*	1	0.092
12	*Gnetumgnemon*	7	0.284	49	*Alstoniaangustiloba*	1	0.025
13	*Dehaasiaincrassata*	6	0.214	50	*Antidesmabunius*	1	0.008
14	*Mimusopselengi*	5	0.012	51	*Archidendronjiringa*	1	0.024
15	*Penoremacanescens*	5	0.058	52	*Artocarpus integer*	1	0.027
16	*Piper baccatum*	5	0.005	53	*Averrhoacarambala*	1	0.001
17	*Dendrocnidecfstimularis*	4	0.005	54	*Caryota sp.*	1	0.001
18	*Ficusvariegata*	4	0.071	55	*Clausenaexcavata*	1	0.005
19	*Nepheliumlappaceum*	4	0.151	56	*Cocos nucifera*	1	0.030
20	*Ficusdeltoidea*	3	0.193	57	*Coffeacanephora*	1	0.001
21	*Ficuselastica*	3	0.278	58	*Derris elliptica*	1	0.058
22	*Ficusracemosa*	3	0.124	59	*Dilleniaindica*	1	0.001
23	*Gliricidiasepium*	3	0.010	60	*Erythrina variegata*	1	0.051
24	*Homalathuspopulneus*	3	0.142	61	*Ficusampelas*	1	0.001
25	*Kompassiaexcelsa*	3	0.128	62	*Ficusbenjamina*	1	0.022
26	*Macaranga diepenhorstii*	3	0.075	63	*Ficusquercifolia*	1	0.004
27	*Quercus sumatrana*	3	0.102	64	*Ficusseptica*	1	0.001
28	*Spondiaspinnata*	3	0.473	65	*Gossypium sp.*	1	0.003
29	*Syzigiumgrandis*	3	0.075	66	*Mischocarpuspentapetalus*	1	0.003
30	*Alstoniascholaris*	2	0.058	67	*Palaquiumrostratum*	1	0.019
31	*Anthocephaluscadamba*	2	0.005	68	*Payenaacuminata*	1	0.002
32	*Artocarpusheterophyllus*	2	0.075	69	*Pometiapinnata*	1	0.020
33	*Baccaureadulcis*	2	0.007	70	*SchimawaliciiKorth.*	1	0.003
34	*Bambusa sp.*	2	0.086	71	*Syzygiumaromaticum*	1	0.001
35	*Caralliabrachiata*	2	0.045	72	*Terminalia catappa*	1	0.179
36	*Celtissumatrana*	2	0.005	73	*Toonasureni*	1	0.021
37	*Diospyros cauliflora*	2	0.031	Total		675	35.117

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Appendix 6. Plant species diversity on Pahmungan Village plot samples.

Site	Plot	Species Richness		Shannon-Wiener index		Simpson index	
		Tree	Middle tree	Tree	Middle tree	Tree	Middle tree
Pahmungan	1	16	4	1.99	1.39	0.75	1.00
	2	11	5	1.16	1.61	0.45	1.00
	3	5	6	0.89	1.67	0.44	0.99
	5	5	5	0.75	1.30	0.35	0.97
	9	6	3	1.27	0.87	0.67	0.99
	10	5	3	0.82	1.04	0.40	1.00
	11	5	2	0.81	0.69	0.39	1.00
	12	5	5	0.75	1.48	0.35	0.99
	13	8	2	1.50	0.64	0.71	1.00
	14	10	5	1.77	1.56	0.75	1.00
	15	8	2	1.28	0.69	0.57	0.99
Total		38	25	1.69	2.99	0.63	0.96

Appendix 7. Plant species diversities on Gunung Kemala Village plot samples.

Site	Plot	Species Richness		Shannon-Wiener index		Simpson index	
		Tree	Middle tree	Tree	Middle tree	Tree	Middle tree
Gunung Kemala	4	11	6	1.67	1.75	0.70	1.00
	6	12	8	2.08	1.84	0.84	0.97
	7	10	7	2.11	1.89	0.90	0.99
	8	4	5	0.75	1.61	0.44	1.00
	16	10	3	1.67	1.04	0.73	1.00
	17	5	4	1.02	1.39	0.53	1.00
	18	6	3	1.54	1.04	0.79	0.99
	19	4	2	0.90	0.69	0.50	0.98
	20	4	3	1.14	1.04	0.67	0.89
Total		28	28	1.97	3.06	0.58	0.95

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Appendix 8. Plant species diversities (Species richness, Shannon-Wiener index and Simpson index) of trees species (> 5 cm of DBH).

No.	Species	H'	D	No.	Species	H'	D
1	*Shorea javanica*	0.344484	0.256340	38	*Elateriospermumtapos*	0.017249	4.4E-06
2	*Lansiumdomesticum*	0.242352	0.011874	39	*Eugenia malaccensis*	0.017249	4.4E-06
3	*Duriozibethinus*	0.167457	0.003429	40	*Eugenia polyantha*	0.017249	4.4E-06
4	*Parkiaspeciosa*	0.088702	0.000528	41	*Lithocarpusspicatus*	0.017249	4.4E-06
5	*Arengapinnata*	0.084592	0.000462	42	*Mangiferacaesia*	0.017249	4.4E-06
6	*Eugenia polycephala*	0.07607	0.000343	43	*Myristicacelebica*	0.017249	4.4E-06
7	*Pterospermumjavanicum*	0.07607	0.000343	44	*Pithecellubiumcypearia*	0.017249	4.4E-06
8	*Areca catechu*	0.052566	0.000123	45	*Tetramelesnudiflora*	0.017249	4.4E-06
9	*Parastemonurophyllum*	0.052566	0.000123	46	*Vitex avinata*	0.017249	4.4E-06
10	*Pithecellobiumjiringa*	0.052566	0.000123	47	*Albiziasaman*	0.009651	0
11	*Bischofiajavanica*	0.04738	9.23E-05	48	*Aleuritesmoluccana*	0.009651	0
12	*Gnetumgnemon*	0.04738	9.23E-05	49	*Alstoniaangustiloba*	0.009651	0
13	*Dehaasiaincrassata*	0.041982	6.59E-05	50	*Antidesmabunius*	0.009651	0
14	*Mimusopselengi*	0.036335	4.4E-05	51	*Archidendronjiringa*	0.009651	0
15	*Penoremacanescens*	0.036335	4.4E-05	52	*Artocarpus integer*	0.009651	0
16	*Piper baccatum*	0.036335	4.4E-05	53	*Averrhoacarambala*	0.009651	0
17	*Dendrocnidecfstimularis*	0.030391	2.64E-05	54	*Caryota sp.*	0.009651	0
18	*Ficusvariegata*	0.030391	2.64E-05	55	*Clausenaexcavata*	0.009651	0
19	*Nepheliumlappaceum*	0.030391	2.64E-05	56	*Cocos nucifera*	0.009651	0
20	*Ficusdeltoidea*	0.024072	1.32E-05	57	*Coffeacanephora*	0.009651	0
21	*Ficusracemosa*	0.024072	1.32E-05	58	*Derris elliptica*	0.009651	0
22	*Ficuseelastica*	0.024072	1.32E-05	59	*Dilleniaindica*	0.009651	0
23	*Gliricidiasepium*	0.024072	1.32E-05	60	*Erythrina variegata*	0.009651	0
24	*Homalathuspopulneus*	0.024072	1.32E-05	61	*Ficusampelas*	0.009651	0
25	*Kompassiaexcelsa*	0.024072	1.32E-05	62	*Ficusbenjamina*	0.009651	0
26	*Macaranga diepenhorstii*	0.024072	1.32E-05	63	*Ficusquercifolia*	0.009651	0
27	*Quercus sumatrana*	0.024072	1.32E-05	64	*Ficusseptica*	0.009651	0
28	*Spondiaspinnata*	0.024072	1.32E-05	65	*Gossypium sp.*	0.009651	0
29	*Syzigiumgrandis*	0.024072	1.32E-05	66	*Mischocarpuspentapetalus*	0.009651	0
30	*Alstoniascholaris*	0.017249	4.4E-06	67	*Palaquiumrostratum*	0.009651	0
31	*Anthocephaluscadamba*	0.017249	4.4E-06	68	*Payenaacuminata*	0.009651	0
32	*Artocarpusheterophyllus*	0.017249	4.4E-06	69	*Pometiapinnata*	0.009651	0
33	*Baccaureadulcis*	0.017249	4.4E-06	70	*Schimawalicii*	0.009651	0
34	*Bambusa sp.*	0.017249	4.4E-06	71	*Syzygiumaromaticum*	0.009651	0
35	*Caralliabrachiata*	0.017249	4.4E-06	72	*Terminalia catappa*	0.009651	0
36	*Celtissumatrana*	0.017249	4.4E-06	73	*Toonasureni*	0.009651	0
37	*Diospyros cauliflora*	0.017249	4.4E-06	Total		2.368884	0.725645

Appendix 9. Regression analyses between spectral reflectance of Landsat-7 ETM+ and the aboveground carbon (ton C/ha) in the 20 sample plots.

Band Ratios	Equations	R^2	Adj. R^2	F Stat.	p-value	RMSE (ton/ha)
Reflectance band 1	705.9 – 5746.4 band 1	0.29	0.26	7.97	0.01	58.87
Reflectance band 2	525 – 4601.5 band 2	0.40	0.37	12.78	0.002	54.78
Reflectance band 3	325.37 – 2803.35 band 3	0.40	0.37	12.59	0.002	54.51
Reflectance band 4	-151.1 + 2091.8 band 4	0.32	0.28	8.93	0.008	58.37
Reflectance band 5	376.8 – 1522.8 band 5	0.37	0.33	11	0.004	56.17
Reflectance band 7	267.83 – 1625.5 band 7	0.44	0.41	14.88	0.001	52.84
Reflectance band 1, 2, 3, 4, 5, and 7	-377 + 11695.7 band 1 – 12241.7 and 2 + 8780.1 band 3 + 2407.1 band 4 – 2722 band 5 – 1730 band 7	0.70	0.57	5.37	0.004	45.22
Reflectance band 1, 2, 3, 4, and 5	-357.8 + 12293.9 band 1 – 12460.2 band 2 + 6802.9 band 3 + 2631.8 band 4 – 3400.8 band 5	0.70	0.60	6.68	0.002	44.20

Appendix 10. Regression analyses between vegetation indices and the aboveground carbon (ton C/ha) in the 20 sample plots.

Vegetation Indices	Equations	R^2	Adjusted R^2	F Stat.	p-value	RMSE (ton/ha)
Simple Ratio 4/3	35.67 + 42.3 SR4/3	0.27	0.23	7.07	0.015	60.21
Simple Ratio 7/3	No Significant	0.15	0.11	3.356	0.083	65.02
NDVI	22.24 + 311.44 NDVI	0.36	0.32	10.82	0.004	56.29
SAVI	29.50 + 653.23 SAVI	0.38	0.35	11.64	0.003	55.54
Brightness	No Significant	0.001	-0.05	0.019	0.889	70.49
Greenness	153.6+1588.9 Greenness	0.39	0.36	12.38	0.002	54.88
Wetness	396.51 + 3401.62 Wetness	0.32	0.29	9.124	0.007	57.97
TNDVI	-395.8 + 577 TNDVI	0.38	0.34	11.49	0.003	55.68
ND74	No Significant	0.15	0.11	3.44	0.079	64.89
Ratio327	No Significant	0.09	0.04	1.92	0.18	67.22

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Appendix 11. Regression analyses between combination of spectral band, vegetation indices, and aboveground carbon (ton C/ha) in the 20 sample plots.

Vegetation Indices/Band Ratios	Equations	R^2	Adjusted R^2	F Stat.	p-value	RMSE (ton/ha)
Band2, 3, 5, 7, Greenness, TNDVI, SR4/3, SAVI, NDVI	No Significant	0.65	0.37	2.328	0.09	54.39
Band 7, TNDVI, SAVI	2436.7 – 3877.9 Band7 – 2499.6 TNDVI + 1939 SAVI	0.55	0.47	6.864	0.003	50.14
Band 7, SAVI	203 – 1243.8 Band 7 + 187.7 SAVI	0.45	0.38	7.265	0.004	53.90