4. LAND USE CHANGE IN NUNUKAN: ESTIMATING LANDSCAPE LEVEL CARBON-STOCKS THROUGH LAND COVER TYPES AND VEGETATION DENSITY

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Introduction

Background

Forests harbour large carbon stocks. Undoubtedly, Kalimantan as one of the largest islands in Indonesia and with vast areas of forest left but a rapid rate of decline in forest cover as well as forest quality, has become a major focus in discussions on the dynamics of forest cover and the impacts on carbon stocks and carbon sequestration.

The FORMACS project of CARE Indonesia in Kabupaten Nunukan was established to test community based forest management as an approach to enhance local livelihoods and reduce negative current trends of forest cover change. Carbon-stock monitoring is needed to evaluate the effectiveness of the project approach towards the goals and to establish a baseline of the rate of change before the project became fully effective.

Remote sensing approaches are an effective way to monitor landscape changes over time. By integrating the changes in vegetation cover with carbon stocks measurements at plot level, changes in carbon stocks at a landscape level can be estimated. Two methods used for such studies: (i) approaches that relate quantitative pixel-level information to carbon stocks as a basis for spatial extrapolation, and (ii) approaches that first classify the land cover according to land use units and then convert to carbon stocks on the basis of properties of the land use units.

Both methods have strengths and weaknesses, and mixed approaches are possible. This study applied both approaches and assessed the level of uncertainty in both.

Objectives

The objectives of this study are:

- Analyze land cover changes from 1996 to 2003 for Kabupaten Nunukan by comparing two independent remotely-sensed-derived land cover maps for the respective years.
- Produce vegetation density maps through the analysis of a Normalised-Difference Vegetation Index (NDVI) of the remotely sensed data.
- Relate the observation points of carbon-stock measurement to the NDVI at pixel level as a basis for spatial extrapolation to the whole landscape.
- Relate mean carbon stock estimates per land cover class to the changes in land cover for an alternative assessment of landscape level carbon stocks
- Assess the strengths and weaknesses of both approaches on the basis of the ncertainty in the underlying relationships,

to advise on the method to be used in future work.

Study Site

Kabupaten Nunukan is located at the northeastern-most part of East Kalimantan province, covering six subdistricts (kecamatan), i.e Krayan, Lumbis, Sebuku, Sembakung, Nunukan and Sebatik (Figure 1.1). Most of Kabupaten Nunukan consists of the Sembakung and Sebuku river basins (each with an 'upland' and 'lowland/coastal' Kecamatan Lumbis-Sembakung and Sebuku-Nunukan, respectively). The western most subdistrict, Krayan, drains to Malinau district and is not accessible from the two main rivers of Nunukan (Figure 4.1). It has a different dynamic of forest cover change. For the more detailed discussion of carbon stocks we will focus on the Sembakung and Sebuku river basins.

Data

Image data used

Multitemporal Landsat images were used to produce land cover maps of Kabupaten Nunu-kan. Acquisition date of each image is shown in table 4.1. Satellite image coverage over Kabupaten Nunukan area is shown in figure 4.2.

Spatial and spectral characters

Spatial resolution of Landsat images is 30 m with 7 spectral channels, ranging from 0.45-0.69 m in the visible spectrum and 0.76-2.35 m in the infrared spectrum. Each band represents different characteristics of wavelengths used to capture features on the earth surface (Table 4.2.).

Table 4.1 Image acquisition dates

Image path/row	Series 1: Landsat 5/ETM	Series 1: Landsat 7/ETM
117/057	December 29^{th}, 1996	January 23^{rd} , 2003
118/057	July 13^{th}, 1996	May 22^{nd}, 2003
118/058	August 17^{th}, 1997	May 22^{nd}, 2003

Table 4.2 Landsat image spectral characteristics (Lillesand and Kiefer, 1994)

Channels	Wavelength (µm)	Characteristics and possible application
1	0.45-0.52	Provides increased penetration of water bodies Supports analyses of land use, soil, and vegetation characteristics
2	0.53-0.6	Corresponds to the green reflectance of healthy vegetation Sensitive in the region between the blue and red chlorophyll absorption bands.
3	0.63-0.69	Sensitive to red chlorophyll absorption of healthy green vegetation, therefore it is important bands for vegetation discrimination. Useful for soil-boundary and geological boundary mapping
4	0.76-0.9	Responsive to the amount of vegetation biomass Useful for identification of vegetation types, Emphasizes soil-crop and land-water contrasts
5	1.55-1.75	Sensitive to turgidity - the amount of water in plants. Discriminate between clouds, snow, and ice Able to remove the effects of thin clouds and smoke
6	10.4-12.5	Measures the amount of infrared radiant flux (heat) emitted from surfaces. Used in locating geothermal activity,
7	2.08-2.35	Discriminate between geological rock formations. Effective in identifying zones of hydrothermal alteration in rocks.

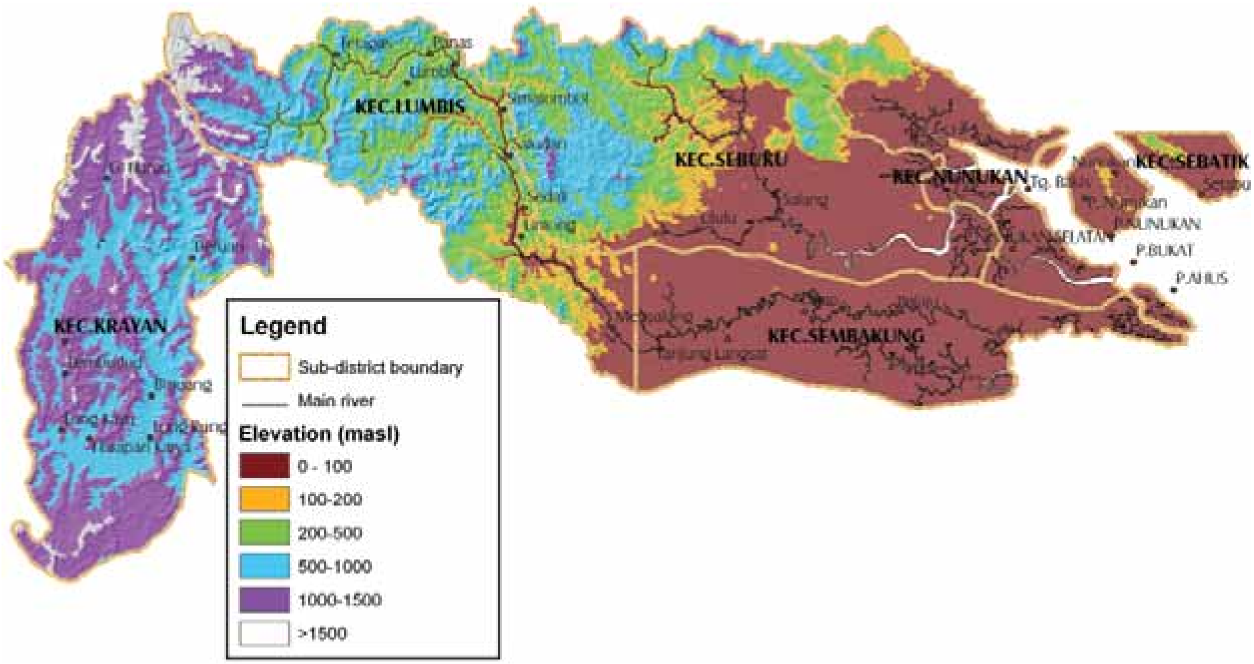


Figure 4.1 Elevation map of Kabupaten Nunukan, East Kalimantan

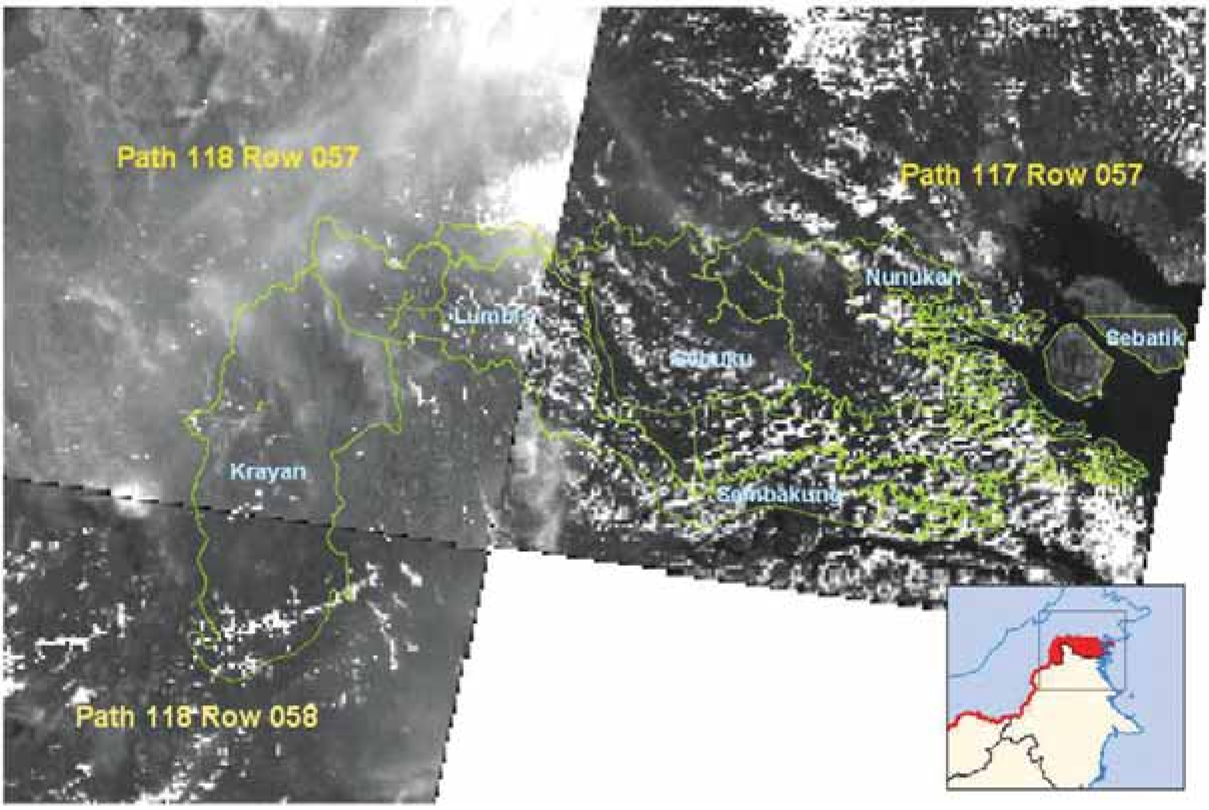


Figure 4.2 Landsat images coverage

Auxiliary Geospatial data (Maps)

Auxiliary geospatial data was required to support the analyses conducted in Kabupaten Nunukan. Four main types of information needed are topography, administrative divisions, geology and land system. Table 4.3 shows the list of maps used in this study.

Methods

Land cover classification and land cover change

Land cover change analysis was conducted on Landsat images using post classification comparison methods where information of changes is derived from multitemporal land cover maps. The flowchart of land cover classification and change detection is shown in figure 4.3.

Image corrections

Radiometric correction

Raw, remotely sensed data captured by a satellite, provide information about object's reflectance at the surface of the earth, which are scaled to a range of number called Digital Counts (DC) or Digital Numbers (DN). Along with the scaling process, some distortion is caused by atmospheric scattering, variation in viewing angle, scene illumination, and instrument response characteristic (Lillesand and Kiefer, 1994 and Chavez, 1996). Practically, the objective of a radiometric correction is to remove the radiometric noises mentioned above.

Geometric correction

Satellite images usually contain geometric distortion caused by several factor ranging from variations in altitude, satellite attitude, and velocity of the sensor platforms, to factors such as panoramic distortion, earth curvature, atmospheric refraction, relief displacement and non-linearities in the sweep of a sensor's IFOV (Instantaneous Field of View) (Lillesand and Kiefer, 1994). To correct the distortion, a geometric correction has to be conducted. Assuming that geometric distortion on images used in this research are non-systematic distortions, geometric correction was carried out by establishing mathematical relationship between pixels in the image and the corresponding coordinates of those pixels on the ground. The mathematical relationship was established based on a set of Ground Control Point (GCP) derived from the topographic map.

Land cover classification

Land cover classification was conducted using supervised classification methods. In supervised classification, training areas are used to define spectral patterns/signature for a specific land cover feature. The signature will then be used by a set of classifiers to identify similar patterns of characteristics over all the area of interest. The result will be an image categorized into a number of land cover types.

Table 4.3 List of maps used in Nunukan study.

No	Title	Scale	Source
1	Topographic map	1:50,000	Dit Top Angkatan Darat
2	Nunukan Spatial Planning Map	-	BAPPEDA Nunukan
3	Geology map	1:250,000	Pusat Penelitian dan Pengembangan Geologi
4	Land System Map	1:250,000	Transmigration Department

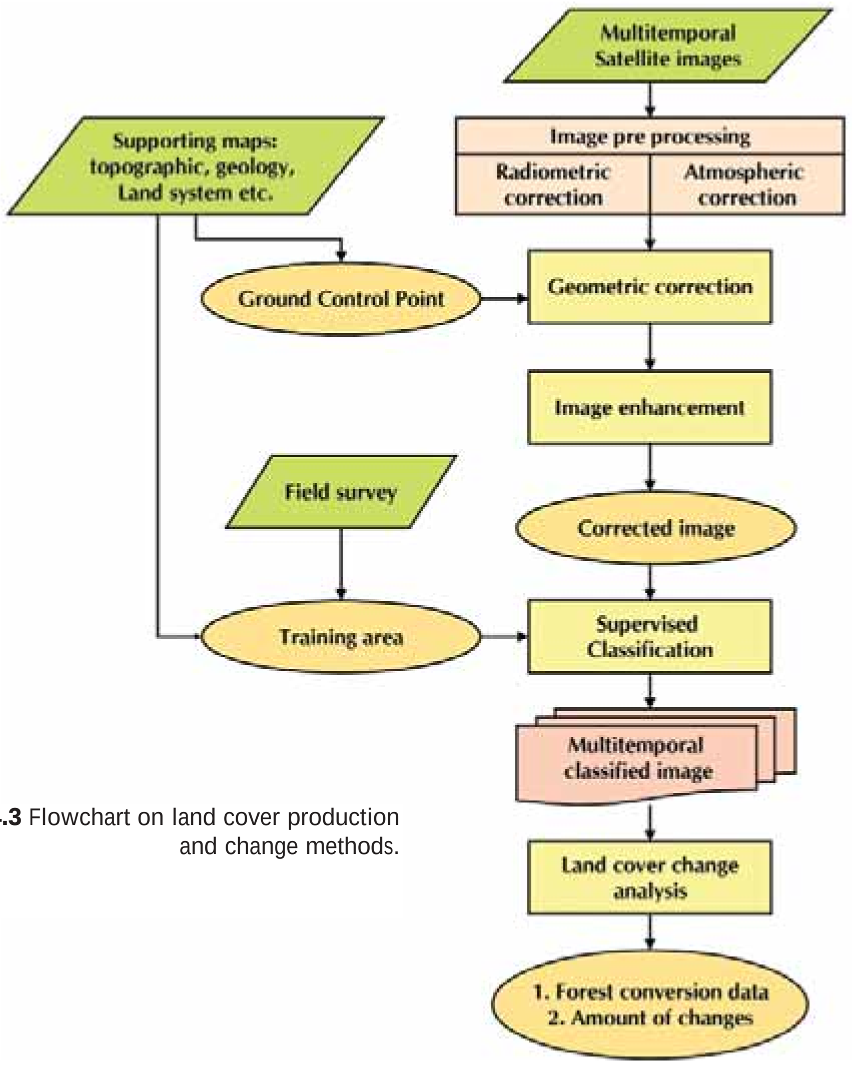


Figure 4.3 Flowchart on land cover production and change methods.

Training samples

Training samples for image classification were obtained during field verification. Global Positioning System (GPS) was used to record the position of training samples. A total of 14 land cover classes were identified during field data collection. The classes are shown in table 4.4.

Table 4.4. Land cover classes

No	Land cover Class
1	Mangrove
2	Primary forest
3	Industrial timber plantation
4	Logged-over forest
5	Secondary forest
6	Old mixed garden (agroforest)
7	Young mixed garden (agroforest)
8	Young oil palm plantation
9	Shrub land
10	Cleared land
11	Settlement
12	Fish ponds
13	Water body

Classification procedures

Classification process to produce land cover map of Nunukan followed a hierarchical classification structure as shown in figure 4.5. The structure divided the classification process into 3 levels where each level utilized a different source of information combining training sample's spectral signature from

Figure 4.4. Land cover types in Nunukan; shrub land (upper left), young oil palm plantation (upper right), fishpond (lower left) and secondary forest (lower right). (*Foto: PT Hatfindo Prima*)

satellite image and supporting information derived from thematic maps.

The first level of the hierarchy aimed to classify land cover classes based only on spectral characters derived from training samples. Two of the classes, however, were lumped and needed to be separated on the second and third level using other information. On the second level the two components of the class "mangrove and primary forest" were separated using thematic information from land system, geological and topographic maps. In the broad group of "secondary forest" a number of distinctions were made: Industrial plantations were identified using industrial concession maps of Kabupaten Nunukan, while old mixed garden was identified using its association with settlement, road and river. Logged-over forest was classified using thematic information from forest concession map of Kabupaten Nunukan and the presence of logging tracks, which are clearly seen in Landsat images. A remnant category of 'secondary forest' was retained. Level 3 of the hierarchy split the logged over forest category into classes, using additional information derived from monitoring sample plots in Kabupaten Nunukan.

Land cover change detection

Land cover change was detected by using the post classification comparison method (Sunar, 1998). The 1996 and 2003 classified images of Kabupaten Nunukan were overlaid and compared to be able to quantify the changes.

Vegetation density mapping

In satellite images, the spectral response is primarily sensitive to vegetation density (leaf

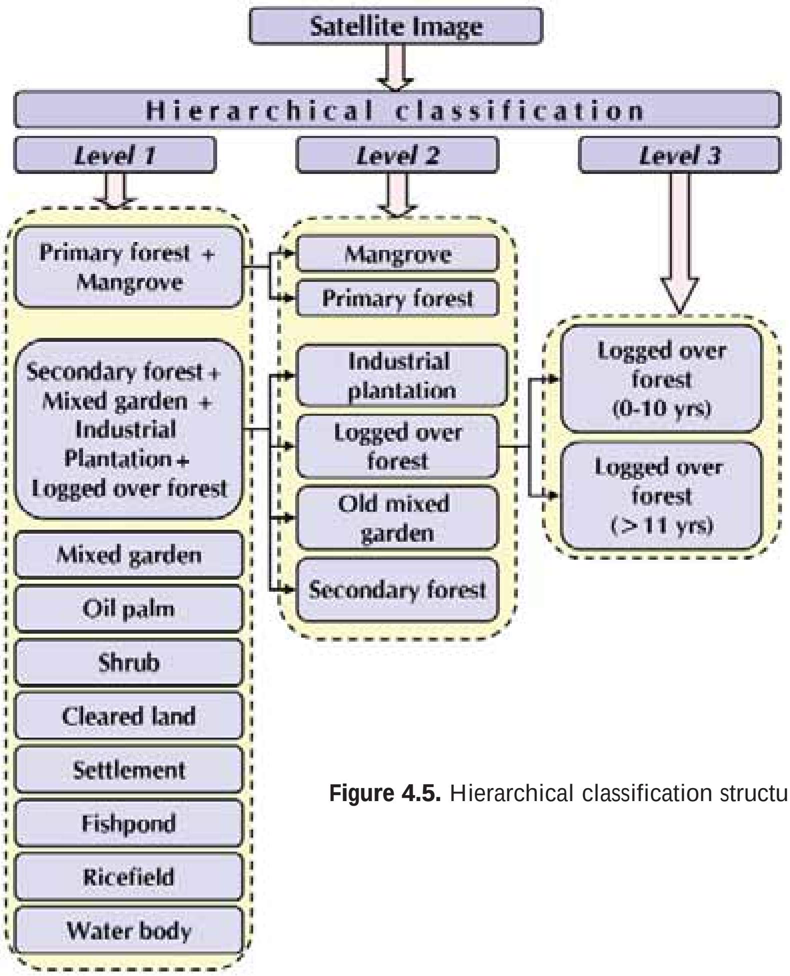


Figure 4.5. Hierarchical classification structure

area index), as well as canopy shading and leaf moisture. As a vegetation develops from open land through various successional stages, visible reflectance decreases in the visible spectrum due to the increased of leaf area and absorption as well as through shadowing both by and within the canopy. The maximum leaf area index is, however, reached much earlier in succession than the maximum tree basal area and tree biomass. On the same circumstances, near infrared reflectance increases due to reflectance from the canopy, transmission throughout the canopy and reflectance of the soil. (Coops, 1996).

The dynamics of visible-infra red spectral response against vegetation density can be well represented by a 'vegetation index' (Huete, 1998). This simple mathematical combination of the Red band and NIR band has been found to be a sensitive indicator of the presence and condition of green vegetation (Lillesand and Kiefer, 1994). While there are several versions of such vegetation indices, the one that was used in this study is the *Normalized Differences Vegetation Index* (NDVI).

NDVI calculation

The NDVI basically measures the slope of the line between the origin of red-NIR space and the red-NIR value of the image pixel. NDVI is calculated using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where NIR=value of near infra red channels; red=value of visible-red channel

The range of NDVI values are -1 to 1. Value of -1 to 0 is usually assumed as non-vegetation.

For this study, NDVI is presented as percentage with the lowest original value (-1) presented as 0 and the highest (1) as 100.

Estimation of land cover under the cloud cover

High cloud cover in the images (up to 40 %) leaves the resulting land cover map with a "No data" value, which made it difficult to obtain land cover areas accurately and which especially created large gaps in the land cover change analysis (as clouds covered different areas in the subsequent images) as needed for landscape level carbon-stock estimation. An approach with GIS techniques was tried to estimate the fraction and area of land cover under the cloud-covered area using Landcover information from the cloud-free area in combination with the other layers of Landsystem and especially Elevation. The flow diagram of the method is presented in Figure 4.6.

Landscape C-stock estimation

Two methods were used for estimating total carbon stocks on the basis of the spatial data. Method one used the land cover information obtained as well as estimated from the procedures above and multiplied the area in each class with the typical aboveground carbon stock density [Mg C ha^{-1}] obtained from Chapter 2 (Rahayu *et al.*, this volume; with a number of additions from the literature for land cover types not sampled locally). Method two established a relationship between pixel level carbon stock and pixel level NDVI as a basis for spatial extrapolation.

Method 1: extrapolation based on land cover map

The two-time snapshot landscape level carbon stock was basically done by re attributing the land cover map of the particular year with corresponding plot-level carbon stock. The expected output was a carbon-stock estimation based on land cover.

The stepwise procedure was:

1. Re-interpretation of the land cover types in the map to the land cover type defined from plot measurement, to find the corresponding definition.
2. Re-attribute the land cover type with the carbon density[1] per land cover type from the plot measurements (table 4.5).
3. Area calculation of each land cover type, to achieve carbon budget for the the Sembakung and Sebuku river basins in Nunukan, for 1996 and for 2003.

Method 2: extrapolation of plots C-stock through vegetation density

To date, there is no method to measure tons of carbon on the ground in landscape level. Correlation between NDVI and ground based data has yielded information about standing biomass and is typically the approach to estimate carbon (Brown, 1996). Studies have been done to estimate biomass or other tree/vegetation biophysical characters using spectral characteristics or transformations of remotely-sensed data. Empirical approaches have found strong relationship between spectral transformations and basal area and (log) tree density (Coops, 1996). Relationship of spectral characters and biomass will reach saturation as canopy closes. Gemmel & Goodenough (1992) in Coops (1996), said that stand basal area continues

[1] Throughout this paper, carbon density is used to describe carbon stocks at plot level, while carbon stocls refer to carbon at landscape level

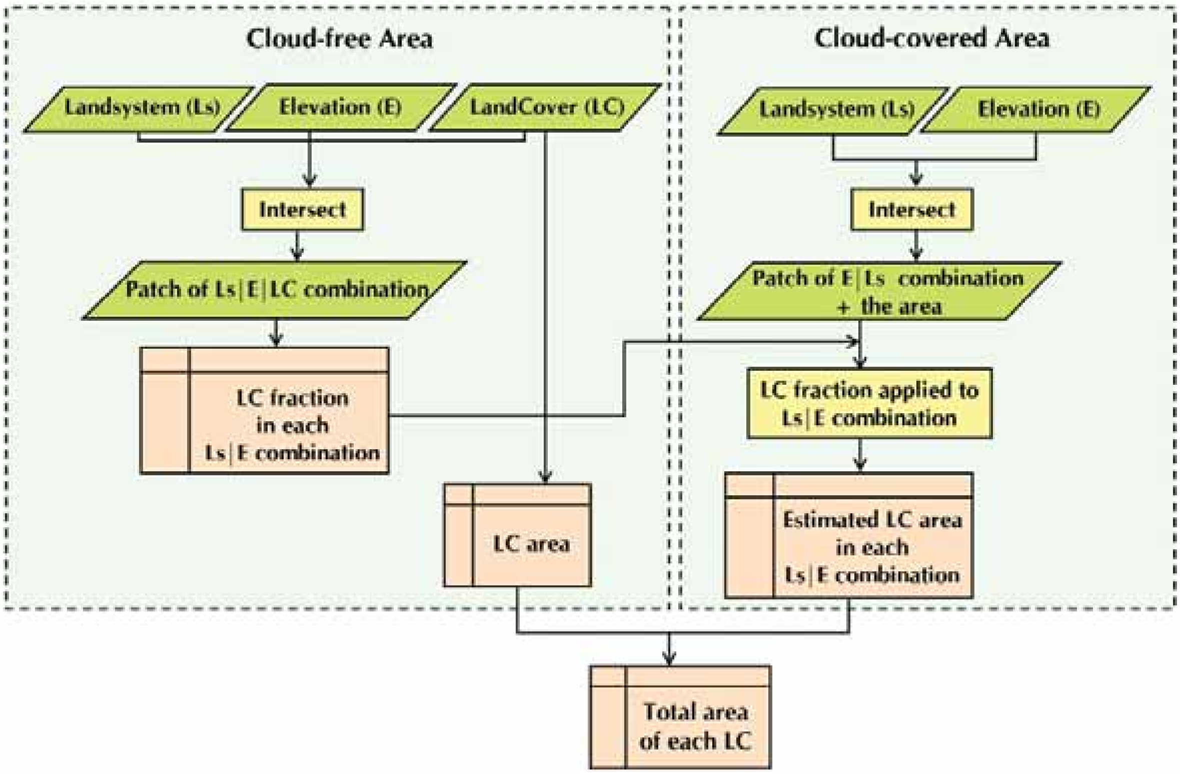


Figure 4.6. Estimation of land cover types under cloud-covered areas

Table 4.5. Re-classification result of carbon stock estimation process (Rahayu *et al.*, this volume)

No.	Land cover type from image classification	Corresponding land cover type at plot measurement	Carbon density (Mg ha^{-1})
1	Primary forest	Primary forest	230.1
2	Logged over forest	Logged over forest	201.3
3	Shrub	Jakaw 0-10 yrs (logged, padi + secondary growth)	19.4
4	Secondary forest	Jakaw > 10 yrs (logged, padi + secondary grwoth)	58
5	Young mixed garden	Agroforestry 0-10 tahun	37.7
6	Old mixed garden	Agroforestry 11-30 tahun	72.6
7	-	Imperata	4.2
8	Industrial plantation	Acacia (Lasco *et al.*, 1999)	88.1
9	Mangrove	Mangrove (Lasco *et al.*, 2000)	176.8
10	Young plantation	Oil palm (Tomich *et al.*, 1998)	91
11	Ricefield	-	
12	Fishpond	-	
13	Cleared land	-	
14	No data	-	
15	Settlement	-	
16	Water body	-	

to increase as the stand grows older but the remotely sensed signal is not affected by this increase because it is most effective to the degree of crown closure which reaches 100% at an early age. As for LAI, relationship between NDVI and LAI is curvilinear and reaches plateau at an LAI of ~6 for coniferous forest (Spanner, Pierce *et al.*, 1996, in Brown, 1996).

The emphasis of this method was to find a relationship between plot level C-stock with the parameter(s) of remotely-sensed data, which is in this case NDVI representing vegetation density. Plot level data on aboveground C stocks are based on four components: tree biomass, understorey vegetation, necromass and litter. NDVI essentially measures the greenness level of vegetation, i.e the leaf components of tree biomass and understorey vegetation. The large fraction of the area with cloud cover and thus absence of NDVI data, restricted the use of method 2 to the cloud-free areas.

The stepwise procedure was:

1. Obtain NDVI values at the positions of the sample plots.
2. Analyze the statistical regression of plot level C stock on NDVI of the associated pixel.
3. Apply the selected regression equation to estimate C stocks in all cloud-free pixels and summarize the results for the the Sembakung and Sebuku river basins in Nunukan, for 1996 and for 2003.

Results and Discussions

Land cover

Land cover 1996

Image classification result of Landsat TM 1996/1997 (figure 4.7) shows that forest was still a dominant land cover type in Kabupaten Nunukan at that time. Classes of primary and secondary forest comprise a total area of almost 9000 km^2 or more than 55% of total area of Kabupaten Nunukan. The total area should be considered as an underestimation as several areas is classified as "no data" due to cloud cover on the satellite image. Mangrove covered more than 5% of the total study area, near the coastline and of Nunukan and Sembakung Sub-districts. The area of "No data" covered almost 28% of total Nunukan's area in the 1996/7 image (table 4.6).

Land cover 2003

Figure 4.8 shows the classification result of Landsat ETM 2003. Cloud cover on the 2003 image was almost 42%, higher than the one in 1996. Primary and secondary forest decreased to about 44% of the district although they are still the dominant land cover types in the area, while shrub increases to 320 km^2 or almost 2% of Nunukan.

Land cover estimation for cloud covered areas

The result of land cover estimation of cloud-covered area using land system and elevation map in 1996 and 2003 is shown in table 4.8, respectively, for the Sembakung and Sebuku river basins, covering approximately 1.1 million ha out of the 1.6 million ha of Kabupaten Nunukan. With cloud-covered removal, in 1996, the area estimation of primary forest increased from 55.6% to 84%; for 2003, the estimated primary forest increased from 28.9% to about 64%.

Land cover changes

Land cover change in the Sembakung and Sebuku river basins in Nunukan over the 1996-2003 period first of all indicates forest conversion. Primary forest decreased from 915,183 ha in 1996 to 697,695 ha in 2003, which means about 24 % of the remaining primary forest disappeared in 7 years (figure 4.9); the equivalent yearly relative conversion

Table 4.6. Area summary of 1996 classified image

CLASS_NAME	Sum km²	%
Water	1263.68	7.9182
Logged over forest	107.35	0.6727
Primary forest	8566.97	53.6809
Secondary forest	396.34	2.4835
Young mixed garden	65.57	0.4108
Old mixed garden	91.50	0.5734
Mangrove	803.37	5.0339
No data	4449.08	27.8781
Settlement	1.20	0.0075
Ricefield	9.05	0.0567
Shrub	124.14	0.7779
Fishponds	7.58	0.0475
Cleared area	73.23	0.4589
Total	**15959.06**	**1**

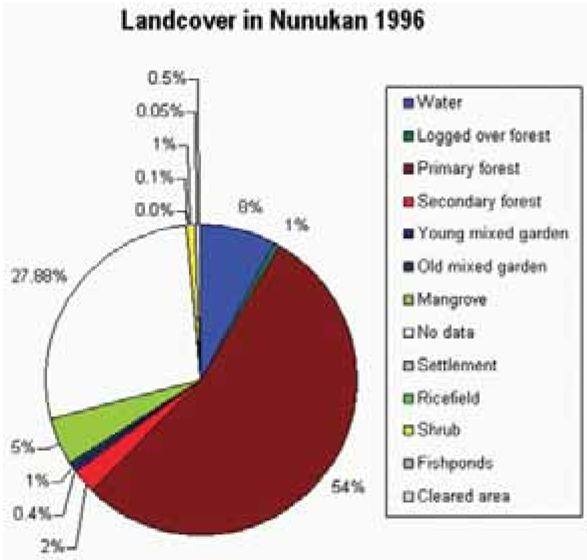
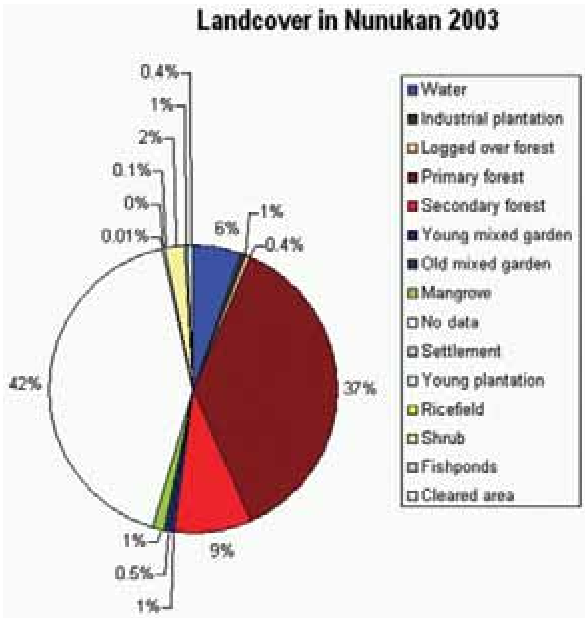


Table 4.7. Area summary of 2003 classified image

CLASS_NAME	Sum km²	%
Water	890.6463	5.58
Industrial plantation	88.9245	0.56
Logged over forest	65.9511	0.41
Primary forest	5865.5493	36.76
Secondary forest	1364.0382	8.55
Young mixed garden	119.3238	0.75
Old mixed garden	73.1916	0.46
Mangrove	228.5811	1.43
No data	6718.2588	42.10
Settlement	1.674	0.01
Young plantation	48.8646	0.31
Ricefield	20.6442	0.13
Shrub	321.3576	2.01
Fishponds	80.1468	0.50
Cleared area	70.2036	0.44
Total	**15957.36**	**100**



rate is 3.85%. A map (figure 4.10) of forest conversion maps suggests that most of the conversion took place close to the main rivers. The mangrove zone was quite stable, covering 6% of the Sembakung and Sebuku river basins along the coastline. The main land cover class that replaced primary forest was the generic 'secondary forest' class, with relatively small increments for industrial timber plantations, shrub and fishponds.

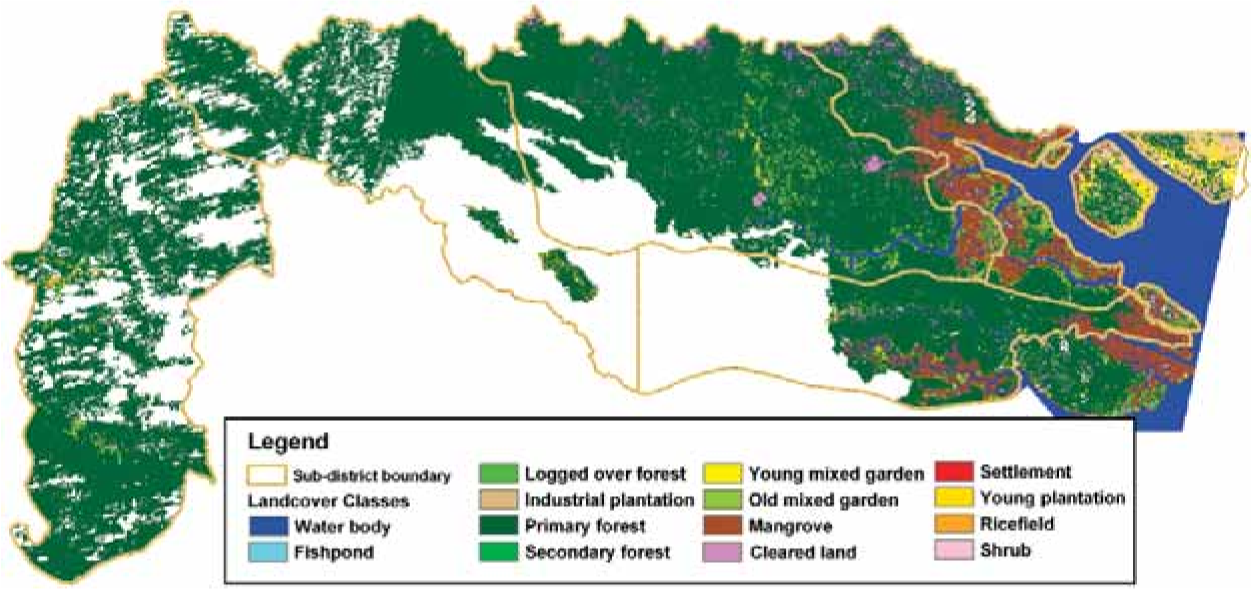


Figure 4.7. Classified image of Landsat 1996/1997

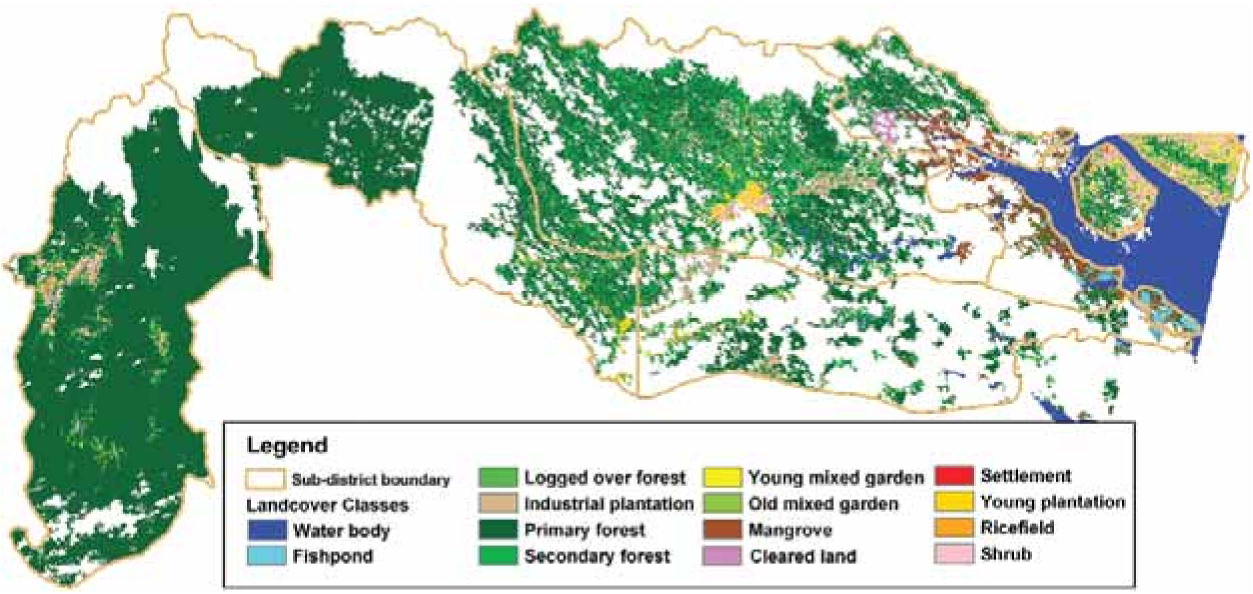


Figure 4.8. Classified image of Landsat 2003

Table 4.8A. Land cover 1996 of Nunukan after cloud removal

Land cover classes	Before cloud removal ha	Before cloud removal %	After cloud removal ha	After cloud removal %
Water body	25641.06	2.35	25886.41	2.38
Logged over forest	8802.26	0.81	8904.11	0.82
Primary forest	606337.99	55.65	915183.03	83.99
Secondary forest	29379.53	2.70	31521.27	2.89
Young mixed garden	6519.73	0.60	7085.34	0.65
Old mixed garden	8248.01	0.76	8978.87	0.82
Mangrove	70190.31	6.44	71532.09	6.56
Settlement	114.13	0.01	114.48	0.01
Shrub	11202.54	1.03	12896.81	1.18
Fishpond	184.97	0.02	185.49	0.02
Cleared land	5977.22	0.55	6615.71	0.61
No data	317041.63	29.10	735.78	0.07
Total	1089639.40	**100**	1089639.40	**100**

Table 4.8B. Land cover 2003 of Nunukan after cloud removal

Land cover Classes	Before cloud removal ha	Before cloud removal %	After cloud removal ha	After cloud removal %
Water	9950.47	0.91	10322.32	0.95
Logged over forest	8982.65	0.82	9244.66	0.85
Industrial plantation	6323.42	0.58	21172.53	1.94
Primary forest	314297.95	28.86	697695.81	64.07
Secondary forest	121823.99	11.19	184554.40	16.95
Young mixed garden	9936.01	0.91	13706.55	1.26
Old mixed garden	5239.42	0.48	5970.62	0.55
Mangrove	22339.35	2.05	67341.96	6.18
Settlement	155.10	0.01	323.71	0.03
Young plantation	4954.62	0.46	9037.78	0.83
Ricefield	942.36	0.09	2361.90	0.22
Shrub	25999.39	2.39	34299.43	3.15
Fishpond	7353.06	0.68	22115.31	2.03
Cleared land	6410.43	0.59	8918.61	0.82
No data	544216.06	49.98	1858.68	0.17
Total	1088924.27	1	1088924.27	

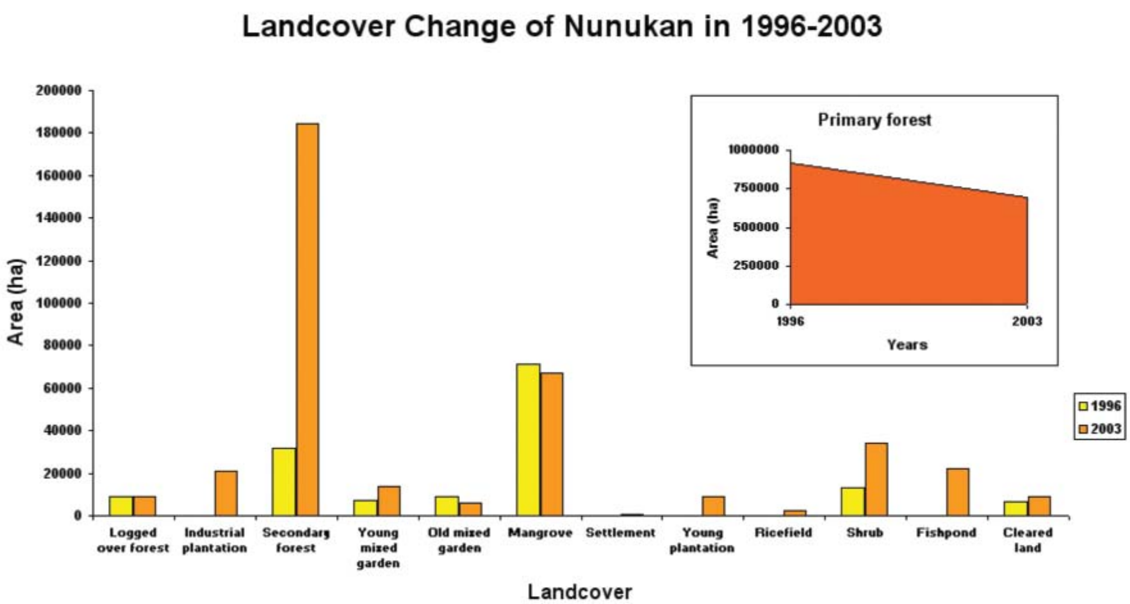


Figure 4.9. Land cover change of Sembakung and Sebuku river basins in Nunukan in 1996-2003

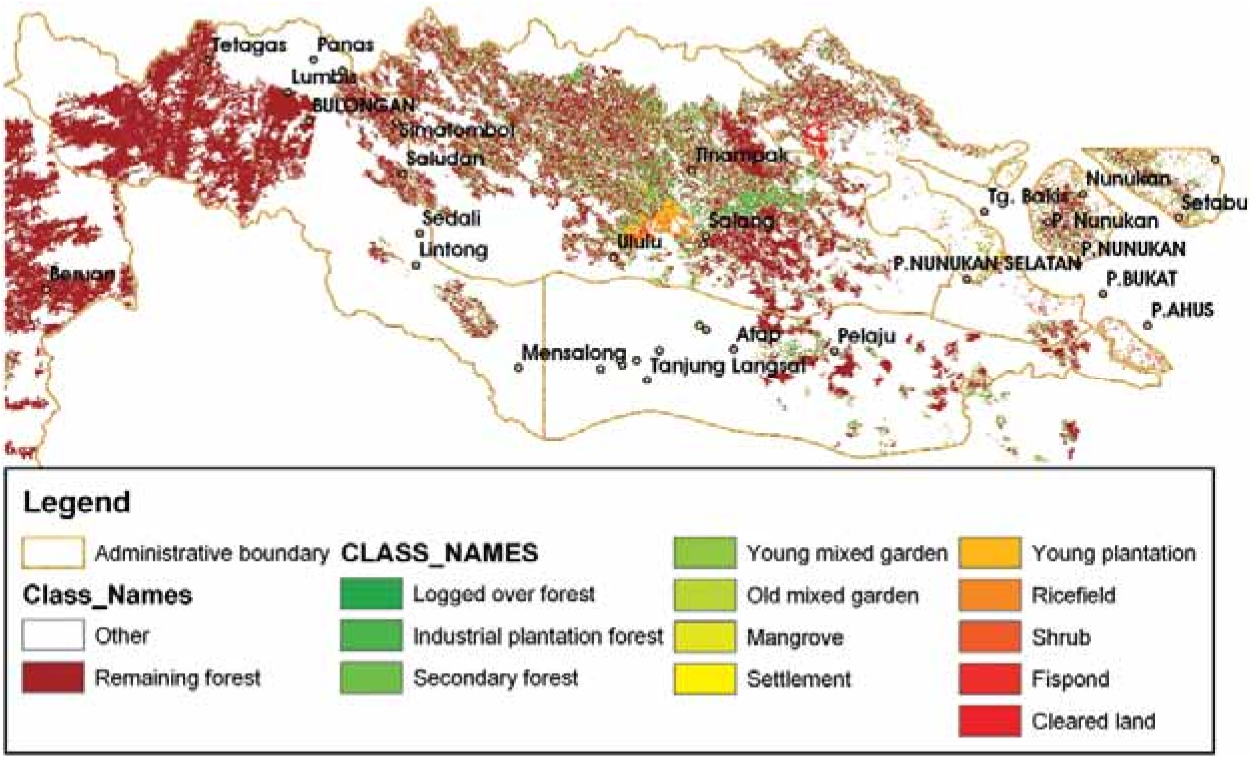


Figure 4.10. Forest change map of Sembakung and Sebuku river basins in Nunukan

Vegetation density

From the NDVI calculation, two NDVI maps are obtained and are shown in Figure 4.11. NDVI varied between 50 and 99, with only very few pixels with NDVI of less than 50 (non-vegetated).

The uneven cloud cover areas of 1996 and 2003 make it difficult to compare the distribution precisely, but large areas in Sebuku with NDVI values in the 70-99 range in 1996 shifted to the 60-70 range in 2003.

Images were not calibrated to various atmospheric and seasonal factors (the east image and west image were from different seasons) and therefore, the range of NDVI resulted was affected.

Difference in season caused a discrepancy in the NDVI calculation, due to different water content of the vegetation, although land cover did not change. Another factor was haze, which caused imperfect NDVI calculation (lower NDVI resulted). This case is clearly seen in west Lumbis with low NDVI (40-50), while most of those areas are still forest.

Landscape C-stock estimation

Land-cover-derived carbon stock estimation

The carbon density map (Figure 4.12) derived from the land cover classes and the typical C densities (Table 4.5) indicates a substantial decrease over the 1996-2003 period, especially along the rivers in the central part of Kecamatan Sebuku.

The total carbon budget estimated from land cover was obtained from the total areas of each land cover types, which include the ones estimated under the cloud cover. In the Sembakung and Sebuku river basins in Nunukan the total carbon stock was approximately 228 Tg[2] in 1996 and 189 Tg in 2003, which means a 17% decrease in seven

[2] 1 Tg= 10^{12} g

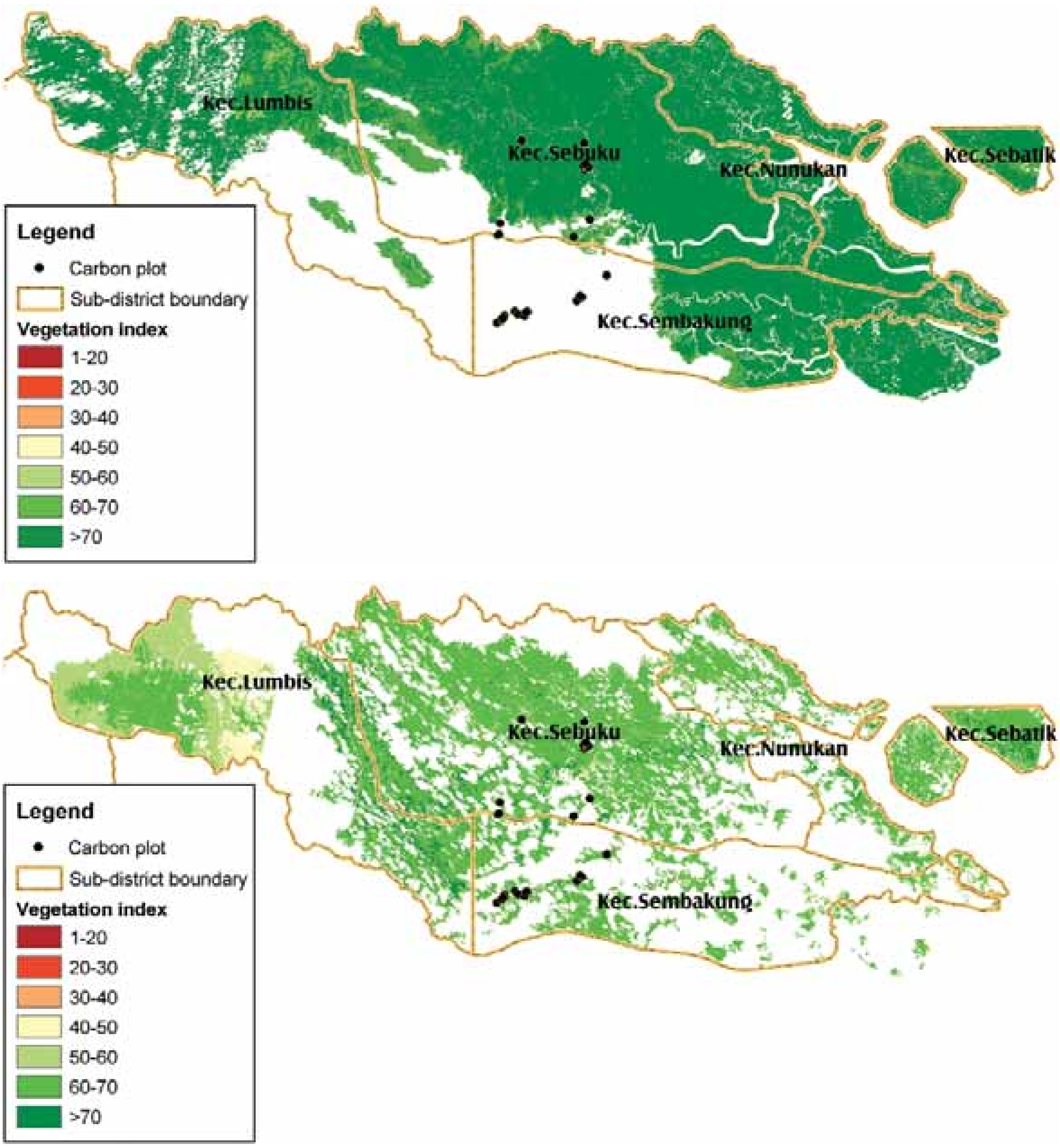


Figure 4.11. Vegetation density (NDVI) in of Sembakung and Sebuku river basins in Nunukan in 1996/7 (upper panel) and 2003 (lower panel) and the distribution of carbon-stock measurement plots.

years. Mean carbon stock density decreased from 209 to 174 Mg ha^{-1}, mostly due to the conversion of 217,000 ha of primary forest to other uses. The loss of C stock (17%) is less than the loss of primary forest (24%).

The geographic distribution of forest conversion, and thus carbon-stock decrease, is hard to be precisely described due to the cloud cover, but in general it can be seen that Kecamatan Sebuku has been experiencing forest loss substantially into *jakaw*, logging and new plantations. In Kabupaten Nunukan, the coastal areas are more or less stable with the existence of mangrove. However, the northern part also shows forest degradation and opening to other uses. These conversions explain the subdistrict's contribution to the decrease of carbon stock.

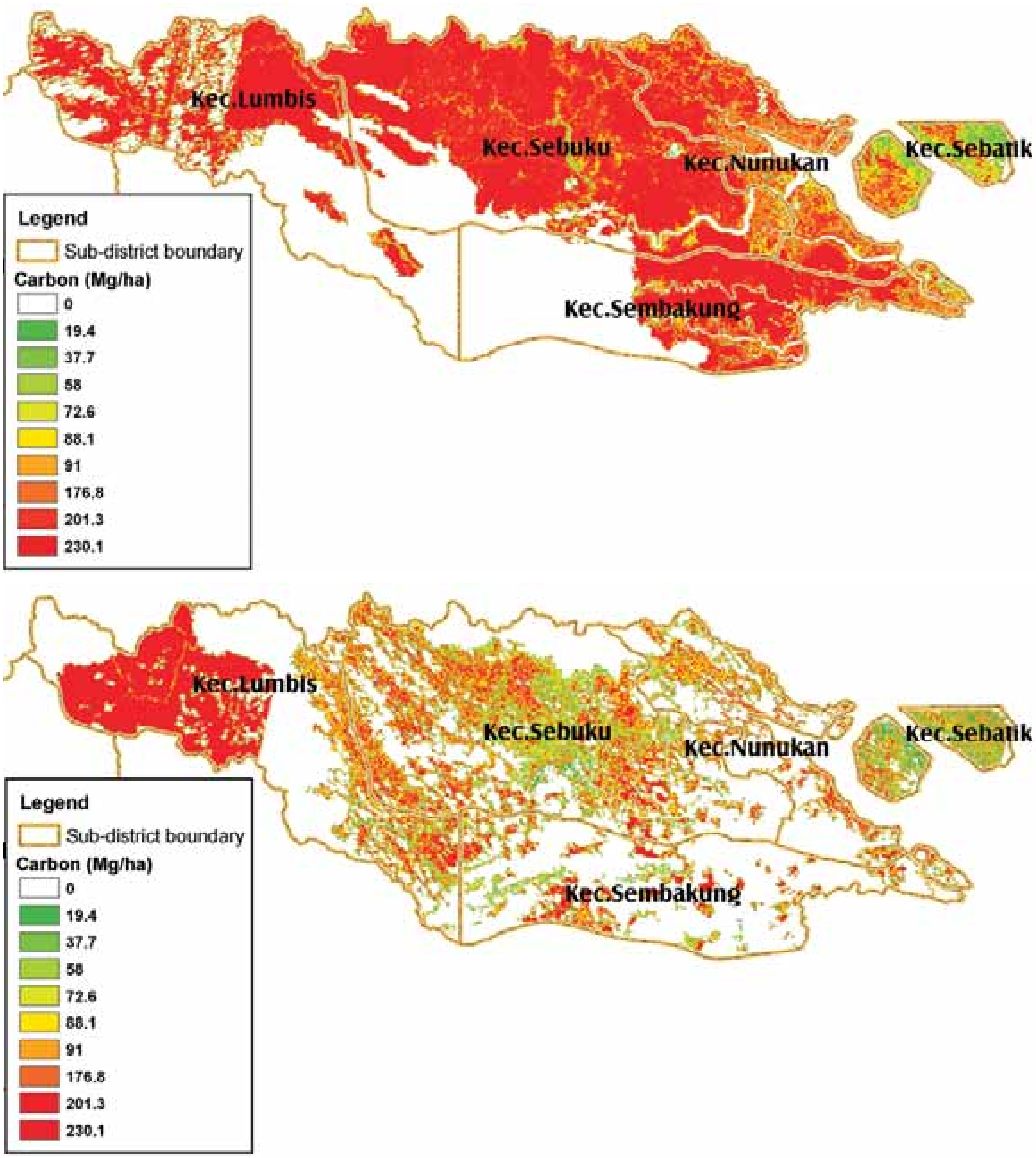


Figure 4.12. Distribution of land cover-derived carbon density in of Sembakung and Sebuku river basins in Nunukan in 1996/7 (upper panel) and 2003 (lower panel).

Vegetation density-derived carbon-stock estimation

Reference carbon density from plot measurements

Only 26 plots in cloud-free areas of the Landsat image could be used for the regression of NDVI on aboveground carbon stock (Appendix 1). The plots with the highest NDVI were agroforest and *Jakaw* left for fallow for > 6 years (NDVI >=69). These high values are expected and come from relatively dense canopy cover from the growing trees in the plot. Logged over forest also had high NDVI (67-69). *Jakaw* plots with a short fallow period corresponded to a wide range of NDVI values (45 - 67). Unfortunately, all the forest plots are located under the cloud-covered areas, and no NDVI values of those plots can be obtained. Relationship between plot carbon density and NDVI values are presented in Figure 4.13.

The relationship between NDVI and carbon stock was distinctly curvilinear and a logarithmic transformation of the C stock data was needed to meet the assumption for standard regression analysis of uniform variability. While carbon density keeps increasing with increments of woody biomass and growth of trees, NDVI values show saturation at the values of 70 as leaf area index reach a maximum. For the data set as a whole only 54% of the variation in the logarithm of measured carbon density can be attributed to variation of NDVI values. As the data suggest two phases on the relationship, a restriction of the NDVI range to values above 60 was attempted. This restriction improves the evenness of variation, but reduces the percentage of total variance accounted for. For further calculations the regression equation used was:

Carbon density [Mg ha^{-1}] = $0.0019 * e^{0.1462*NDVI}$

As the exponential equation relates to the logarithm of measured C stock, its use for predicting C stock can be expected to underestimate the mean value. In fact the mean of the 'predicted' value for the calibration points was only 52.8% of the measured values (and 59.7% if the restriction to NDVI > 60 was used). Applying this equation to estimate landscape level carbon will result in underestimation of carbon stock. Although the regression was derived for the NDVI values of 2003, it was applied as such to the 1996/1997 data, ignoring possible differences in NDVI due to season and haziness of the images (Figure 4.14).

Direct comparison with method I is possible only for the cloud free areas, or approximately 738,000 ha for 1996 and 522,000 ha for 2003. For these areas, NDVI-derived carbon stocks suggest a dramatic decrease from 1996 to 2003. In 1996, the average estimated carbon-density was 222 Mg ha^{-1}, while in 2003 it was only 27 Mg ha^{-1} (Table 4.9).

Table 4.9. Comparison of C stock estimates for 1996 and 2003 based on two methods

Year	Land-cover derived average carbon density [Mg ha^{-1}]	NDVI-derived average carbon-density [Mg ha^{-1}]
1996	210	222
2003	166	27

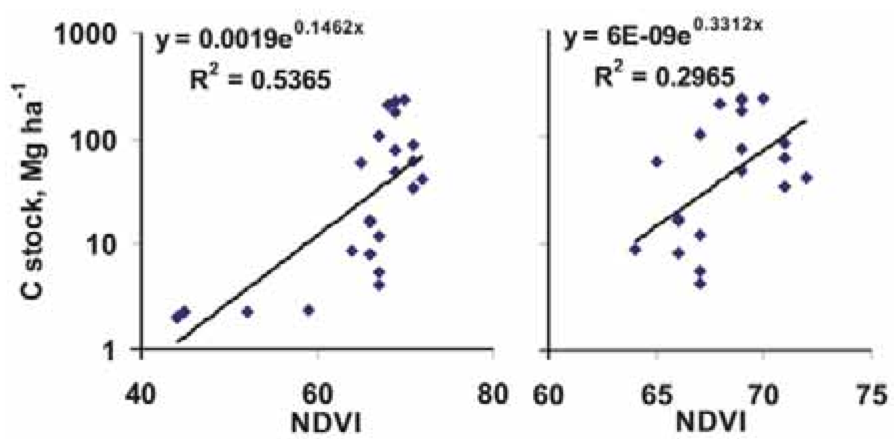


Figure 4.13. Relationship between NDVI and aboveground carbon-stock (logarithmic scale); left panel for the whole data set, right panel restricting the values to NDVI > 60

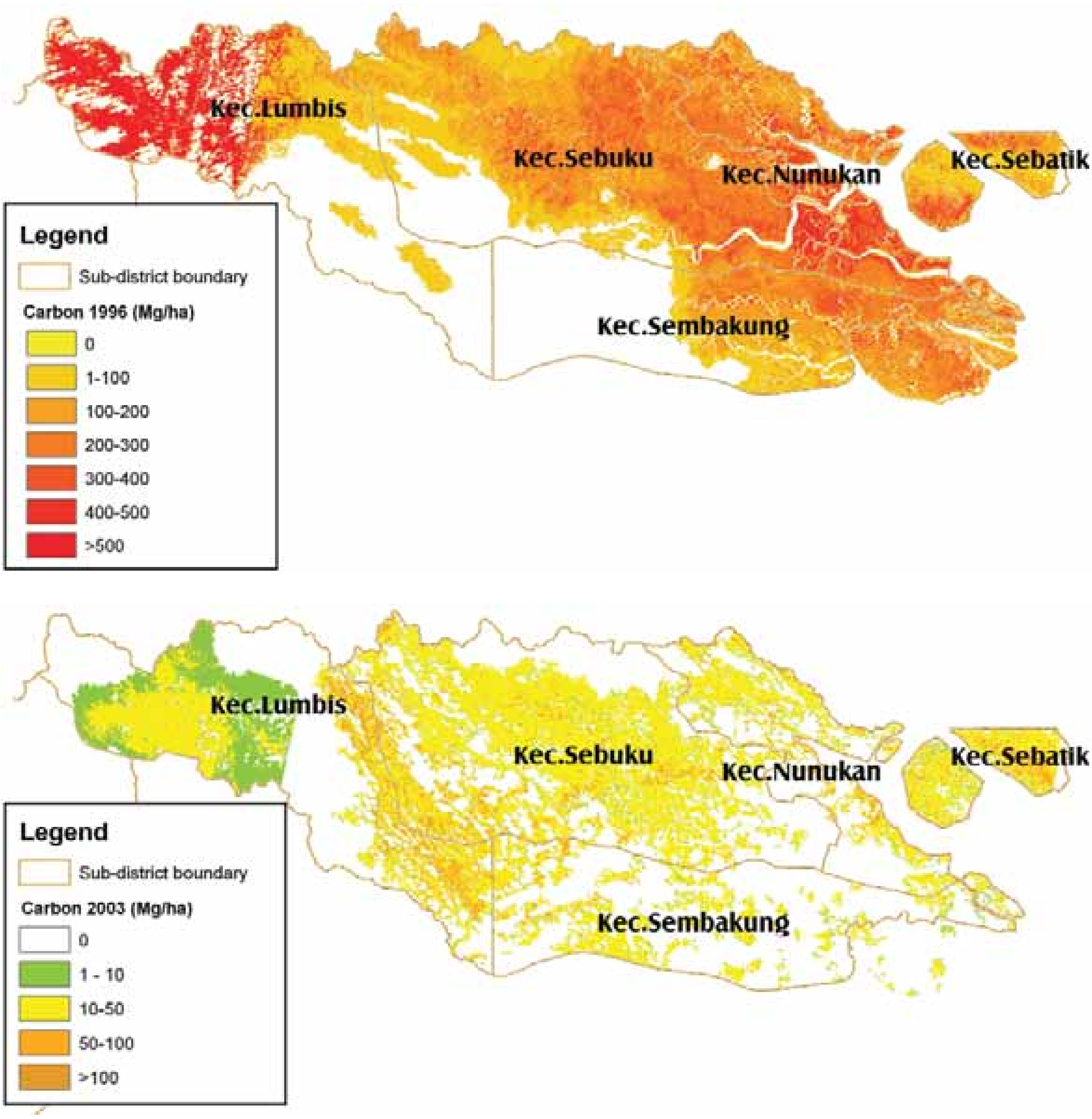


Figure 4.14. NDVI-derived carbon density of the Sembakung and Sebuku river basins in Nunukan in 1996 (upper panel) and in 2003 (lower panel)

Comparing carbon-stock estimates from land cover maps and from vegetation density

For 1996 the results of the mean C density in the cloud-free area show only a slight discrepancy between two methods, while for 2003 a big difference was found. A number of factors may contribute to this difference:

- For NDVI-derived carbon-stock estimation, the results are generally an underestimation, due to the low correlation between NDVI and measured carbon density, and the high variability of carbon density for the high values of NDVI (> 70%), in which carbon density varies from 50 to 250 Mg ha^{-1}. The non-linear aspect of the NDVI-C-stock regression line leads to a bias in the C stock results, as discussed before.
- For the land cover-derived carbon stock, accuracy of the land cover maps still need to be done using ground truth check (with

sample points that have not been used for defining the interpretation key). Verification of the resulted carbon density might also be conducted using independent C-stock measurements.

- The NDVI values for 1996 were considerably higher than those for 2003 due to a difference in season (water content of the vegetation) and general image quality (haziness), also for the forest land cover types that must have been in the same category in 1996 as they were in 2003. Yet, the NDVI regression line was established on 2003 data only and in fact most pixels in the 1996 data series were outside of the calibration domain, requiring extrapolation (with a weakly defined regression line). The similarity in results for 1996 may thus be based on a coincidence, with two types of error canceling each other, rather than on genuine agreement between the methods.

Conclusions

The main conclusions of this study are:

1. Land cover change from 1996 to 2003 in Kabupaten Nunukan has been substantial, with an estimated 3.85% $year^{-1}$ of conversion to other land cover types of the remaining primary forest.
2. Maps of vegetation density based on the Normalised-Difference Vegetation Index (NDVI) suggest an even more drastic change between the two observation times, but a number of technical difficulties with the method (differences in season and haziness of the images) are at least partially responsible for this difference.
3. Carbon-stock estimates based on NDVI at pixel level and a regression line of carbon stock on NDVI differ essentially from those based on spatial extrapolation of the land cover type of sample points to the whole landscape.
4. Using corrections for cloud-covered parts of the landscape, mean carbon stock density in the Sembakung and Sebuku river basins in Nunukan (i.e. the whole district minus the western most subdistrict) decreased between 1996 and 2003 from 211 to 175 Mg ha^{-1}, mostly due to the conversion of 217,000 ha of primary forest to other uses. The loss of C stock (17%) is less than the loss of primary forest (24%), as the resultant land cover types still retain part of the carbon stocks.
5. The main uncertainties in the overall estimates based on land cover types derive from the uncertain nature (and probably large internal variability) of the 'secondary forest' category in the land cover classification, as well as from the possibility of changes with time in typical carbon stock density within the main land cover types (esp. for categories such as 'logged-over' forest or agroforest), linked to changes in the intensity of land use within each of the categories.
6. Although a direct derivation of C stock from the remotely sensed images has theoretical advantages over estimation based on land cover classes, the nature of the relationship between leaf-area based indices such as NDVI and the largely wood-based C stock, make the method very vulnerable in practical application as well as subject to a bias that will require further statistical techniques to be overcome.