Journal of Natural Resources and Environmental Management
13(4): 574–585. http://dx.doi.org/10.29244/jpsl.13.4.574–585
E-ISSN: 2460-5824
http://journal.ipb.ac.id/index.php/jpsl

Assessment of the success of canopy cover revegetation of former coal mine lands with Forest Canopy Density (FCD) Model in Kutai Kartanegara, East Kalimantan

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Article Info:
Received: 16 - 01 - 2023
Accepted: 03 - 05 - 2023

Keywords:
Coal, forest canopy density, mining, reclamation, remote sensing

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Abstract. *Coal mining plays a vital role in Indonesia's economic growth. However, these activities negatively impact the environment. To minimize this, the Indonesian government requires ex-mining land to be reclaimed, with one of the success criteria being canopy cover. Until now, there has been no measurable method that can determine the success rate of canopy cover on reclaimed land. This research was conducted to develop a measurement method based on remote sensing data using the Forest Canopy Density (FCD) Model, which is applied in Company X, Kutai Kertanegara. The FCD Model consisted of four biophysical indices, including AVI, BSI, SI, and TI, obtained from Landsat 8 OLI TIRS imagery from 2013–2021. The Kolmogorov-Smirnov normality test was performed before testing the relationship between FCD values and canopy cover using linear regression to obtain the canopy cover success value based on the FCD value. The FCD showed an increasing trend yearly, especially in the first two years after planting. Regression analysis showed a strong relationship between FCD values and canopy cover values, with* R^2*=0.775, and revealed that 75.35 is the FCD value threshold for a successful canopy cover in the reclamation area. This study shows that the FCD approach can be applied to determine the success rate of reclamation in post-mining areas.*

How to cite (CSE Style 8th Edition):
Rosikin, Prasetyo LB, Hermawan R. 2023. Assessment of the success of canopy cover revegetation of former coal mine lands with Forest Canopy Density (FCD) Model in Kutai Kartanegara, East Kalimantan. JPSL **13**(4): 574–585. http://dx.doi.org/10.29244/jpsl.13.4.574–585.

INTRODUCTION

Mining is one of the most important sectors contributing to a country's economic development (Mohsin et al. 2021; Tiwary 2001), especially for coal commodities. Coal is a major contributor to global power generation, manufacturing, and economic development (IEA 2022). According to BP (2022), the total global production of coal in 2021 is 167.58 exajoules, and coal is the most dominant source of energy in the world, even though global coal consumption has decreased. In Indonesia, the contribution percentage of Gross Domestic Bruto in 2021 to the mining and quarrying sector has reached 8.98%, one of which is influenced by the coal mining sub-sector, which is 3.55% (BPS-Statistics Indonesia 2020). So, it can be said that mining is the most important sector for both the needs of human life and as a source of state income in terms of development. However, mining has another side, which is considered negative. In the mining process, land clearing and excavation are the main activities that must be performed. The existence of mining activities, such as deforestation and forest degradation, has an impact on the biodiversity of flora and fauna. Coal mining activities not only damage the ecosystem within the mining area but also affect the buffer zones around mining activities (Liu et al. 2022).

To reduce the negative impacts of mining activities, the government of Indonesia (2020) requires mining business actors to organize the reclamation of ex-mining land. Following Law No. 3 of 2020, reclamation is an activity carried out throughout the stages of the mining business to organize, restore, and improve the quality of the environment and ecosystem so that they can function again according to their designation. Ex-mining land that has been biogeophysically reclaimed, namely the quality of water, air, and diversity of flora and fauna, has better conditions than mine lands that are still operating or have not been reclaimed (Kurniawan and Surono 2013). For the implementation of reclamation of the results of mining activities to be in accordance with the original purpose and its designation, the Indonesian government annually assesses the success of reclamation by referring to predetermined success criteria.

This is stipulated by Minister of Forestry Regulation No. P.60/Menhut-II/2009 concerning guidelines for evaluating the success of forest reclamation and the decree of the Ministry of Energy and Mineral Resources No.1827K/30/MEM/2018 concerning Guidelines for Implementing Good Mining Principles. One of the criteria specified in the regulation is the condition of canopy cover. Canopy cover was not significantly affected by the type of land conditions at the site but was significantly affected by the age of the site being reclaimed (Frouz et al. 2015). However, in the implementation of canopy cover measurement, there is no measurement method, and it is often subjective in determining the success criteria related to canopy cover. The absence of a measurement method can be one of the causes of disputes between the government as policymakers and mining-sector actors, which will eventually lead to dissatisfaction with the performance of the reclamation success assessment team. In addition, the assessment of reclamation success is also influenced by the size of the reclamation area being implemented: the more reclamation areas that must be assessed, the greater the time and cost required.

Therefore, it is necessary to determine how reclamation assessment can be carried out more effectively and efficiently. This study provides options for determining the success of revegetation with criteria for canopy cover that are more objective, measurable, effective, and efficient. Remote sensing technology can be used with the Forest Canopy Density (FCD) method. Based on Rikimaru (1997), FCD is a calculation method used to calculate the density of vegetation cover by integrating four indices related to the biophysical conditions of forest vegetation. Accurate results can be obtained by applying the FCD model because this method focuses on forest growth phenomena (Rikimaru 1996). Therefore, this will also make it possible to monitor changes in vegetation canopy cover during the reclamation of an ex-mining area over time. Therefore, the purpose of this research was to determine the pattern or trend of changes in the FCD index every year at Company X and determined the success value of the canopy cover of ex-mining land using the FCD value approach at Company X, from this research, it is hoped that it can also be input to the government in carrying out the assessment of the reclamation of ex-mining land.

METHODS

Study Site

Overall, this research was conducted from January 2021 to December 2021, off-site and on-site, in the mining permit area of Company X is located in Kutai Kertanegara Regency, East Kalimantan Province, Indonesia. Geographically, the research location was between 0°24'46”–0°43'54” N and 116°47'10”–117°03'55” E, with an area of 457.01 km^2 which as shown in Figure 1.

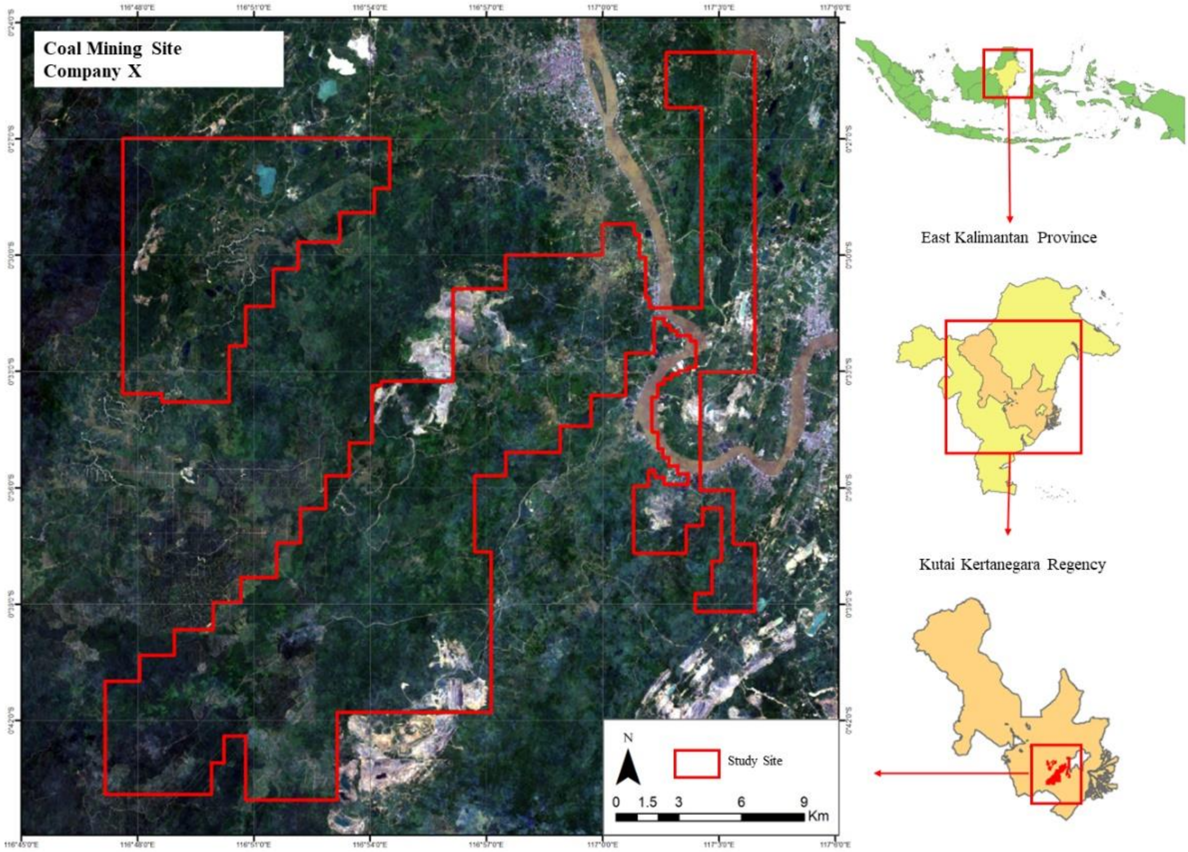


Figure 1 Study site

Data Collection Method

The multiple datasets used in the current study were partially dominated by secondary data and supported by primary data, which is useful for validating the processing results. The secondary data used were multitemporal Landsat 8 OLI TIRS satellite imagery for the period 2014–2021, which was obtained using the Google Earth Engine platform (*https://code.earthengine.google.com/*). In addition, polygons for the multitemporal reclamation area during 2014–2021 were also used, obtained directly from the Company X.

Then, a field survey was conducted between August and October 2021 to obtain data on canopy cover. Canopy cover measurements were obtained by taking hemispherical photos from under the canopy perpendicularly upwards using a DSLR camera with a fisheye lens. Canopy photos were taken on the reclaimed land by making a field measurement plot with 60 grid plots adjusted to Landsat 8 OLI spatial resolution measuring 30 m × 30 m with five photos in each plot. The canopy cover data are shown in Figure 2.

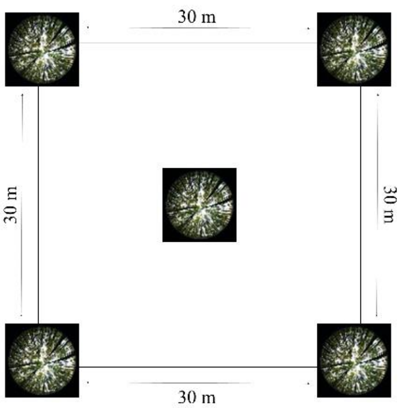


Figure 2 Canopy cover data collection scheme

Data Analysis Method

The following three analysis steps performed the Analysis method in this research: (1) Interpretation of satellite imagery that consists of preprocessing satellite imagery and Forest Canopy Density (FCD) analysis using Google Earth Engine and ArcMap 10.8; (2) Gap fraction analysis was conducted to obtain canopy cover values using the Gap Light Analysis software; (3) Statistical analysis consisting of a normality test using the Kolmogorov-Smirnov (K-S) method, followed by linear regression analysis to obtain a linear regression equation that can estimate the value of canopy cover using the FCD value. Overall, this research is presented in a flow chart (Figure 3).

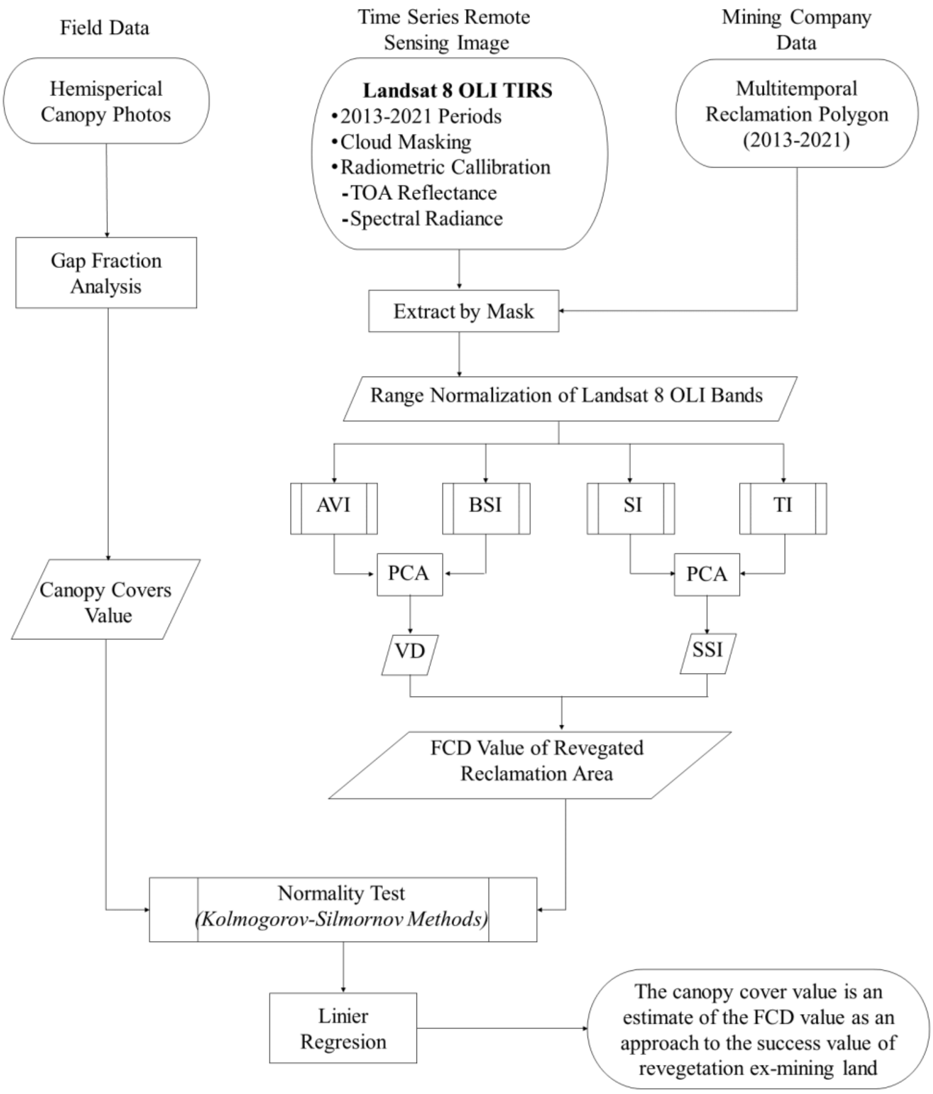


Figure 3 Research workflow

Pre-processing of Satellite Imagery

The acquired Landsat 8 OLI TIRS imagery was radiometrically calibrated and cloud-masked using a median filter. This pre-processing step was performed using Google Earth Engine, a cloud-based satellite imagery analysis platform that enables global-scale processing (Gorelick et al. 2017). Therefore, many mine monitoring studies have been conducted on the GEE platform, including mining and reclamation monitoring in the Sheng-li mine, China (Xiao et al. 2020), monitoring of post-mining recovery in the Didipio mine, Philliphines (Ang et al. 2021), and monitoring of open-pit coal mining disturbance and reclamation in Inner Mongolia, China (Xiao et al. 2023).

Forest Canopy Density (FCD) Analysis

FCD is a calculation model that combines four biophysical indices to represent the vegetation cover density of forests (Rikimaru 1997). The four physical indices are the Advanced Vegetation Index (AVI), Bare Soil Index (BSI), Shadow Index (SI), and Thermal Index (TI), which were derived from Landsat 8 OLI TIRS spectral band calculations. Before calculating the four indices, the pre-processed Landsat 8 OLI imagery was first normalized using linear transformation using Equations:

$$Y = AX + (-AX_1 + Y_1)$$

$$A = \frac{(Y_1 - Y_2)}{(X_1 - X_2)} = \frac{(Y_1 - Y_2)}{(M - 2S) - (M + 2S)}$$

Where:

Y = normalized data	X1 = M – 2S
X = original value	X2 = M + 2S
A = linear transformation	Y2 = minimum value of standardized value
M = mean of values	Y1 = maximum value of standardized value
S = standard deviation	

The next step is to calculate the bio-physical indices, the FCD components listed in Table 1 (Rikimaru 1997; Falensky et al. 2020; Jain et al. 2020). The four indices showed an inverse relationship. As the AVI value increases, which represents the presence of vegetation, it decreases the BSI value, which represents the open area, and vice versa. The same applies to the relationship between SI and TI, where an increase in the SI value indicates a dense forest structure and a decrease in the TI value (Rikimaru 1996, 1997).

Table 1 FCD component equation

FCD components	Formula
Advanced Vegetation Index (AVI)	If B5 – B4 < 0 then AVI = 0 If B5 – B4 > 0 then $AVI = \sqrt[3]{(B5+1) * (65{,}536 - B4) * (B54)}$
Bare Soil Index (BSI)	$BSI = \left(\left[\frac{(B6+B4)-(B5+B2)}{(B6+B4)+(B5+B2)}\right] \times 100\right) + 100$
Shadow Index (SI)	$SI = [(65{,}536 - B2) \times (65{,}536 - B3) \times (65{,}536 - B4)]^{1/3}$
Thermal Index (TI)	$T = \frac{\text{K2}}{\text{Ln}(\frac{\text{K1}}{\text{L}\lambda}+1)}$

Note: B2 = blue band; B3 = green band; B4 = red band; B5 = NIR band; T = temperature; Lλ =radians value; K1 = 774.89 W/(m^2 sr mm); K2 = 1,321.08 K

As an intermediate step before calculating the FCD, AVI and BSI were synthesized into Vegetation Density (VD) parallel with SI, and TI was synthesized into a Scaled Shadow Index (SSI) using Principal Component Analysis (PCA). Subsequently, the PCA images of VD and SSI were normalized to produce a value range between 0 and 100. Finally, the normalized VD and SSI values were integrated to generate the FCD values using equation as follows (Rikimaru 1997):

$$FCD = \sqrt[2]{SSI * VD + 1} - 1$$

Gap Fraction Analysis

Hemispherical photographs of the 60 grid plot samples were used in the gap fraction analysis to obtain canopy cover values. Gap fraction of a canopy is the fraction of view that is unobstructed by the canopy in any particular direction (Welles and Cohen 1996) or in practical definition gap fraction is the ratio between white and all pixels of a segment of a hemispherical photograph classified to black and white (Tichý 2016). The Gap Light Analyzer (GLA) v.2.0 software developed by Frazer et al. (1999) was used to analyze the gap fraction. From the gap fraction analysis, it is possible to derive the canopy cover value, which is used in the linear regression along with the FCD value.

Statistical Analysis

Linear regression analysis was performed to model the relationship between the FCD value and canopy cover value. Before linear regression is executed, it is necessary to test the normality of the data using the Kolmogorov-Smirnov (K-S) method. Regression analysis was executed if the data were normally distributed with a significant value greater than 0.05. All statistical analyses were performed using Microsoft Excel 2019 and the Statistical Package for the Social Sciences (SPSS) Software. Then, the producer, user, and overall accuracies were calculated based on a comparison between the classification results and field observations in the form of a confusion matrix.

RESULT AND DISCUSSION

Forest Canopy Density Trends

The forest canopy density map was generated by integrating the AVI, BSI, SI, and TI using the procedure described in Table 1. Each index was calculated by applying the procedure to every Landsat 8 OLI TIRS image every year from 2013 to 2021. The samples of the multitemporal forest canopy density map of the study area reclamation site is shown in Figure 4.

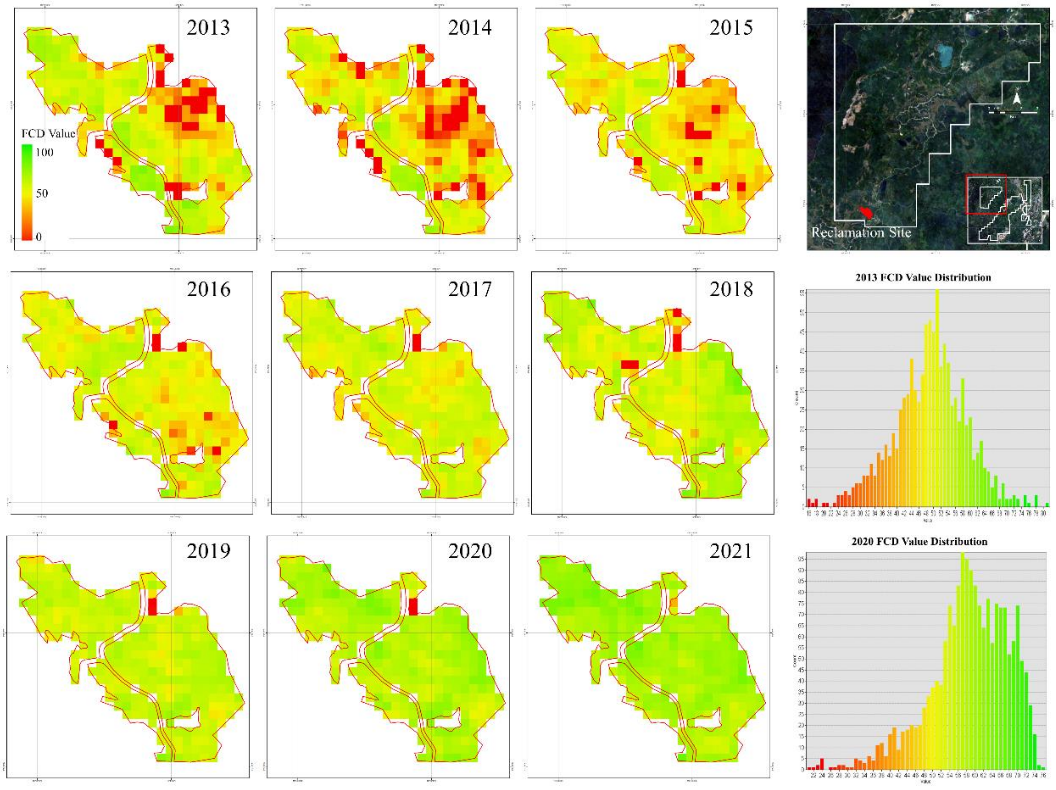


Figure 4 Forest canopy density map of a reclamation site

Figure 4 shows the dynamics of changes in FCD values in one of the reclaimed lands with the planting year 2013 during the 2013–2021 period, which has a trend that tends to increase every year. Generally, the FCD value in the year of the first planting spread normally with mode number 51, while in 2020 the FCD value significantly shifted to the right, which means that the FCD value increased. In 2020, the centered value was 54–72 with a mode of 58, as shown by the graph in Figure 4. Partially to observe changes in FCD values over time, this study generated 50 random points in the reclamation area of the planting year 2013 as sample points. The results showed that the change in the FCD value from 2013 to 2021 experienced an increase that specifically increased dramatically when the plants were 2 years old since planting with an average FCD value of 56 in the second year and began to slow down the following year (Figure 5).

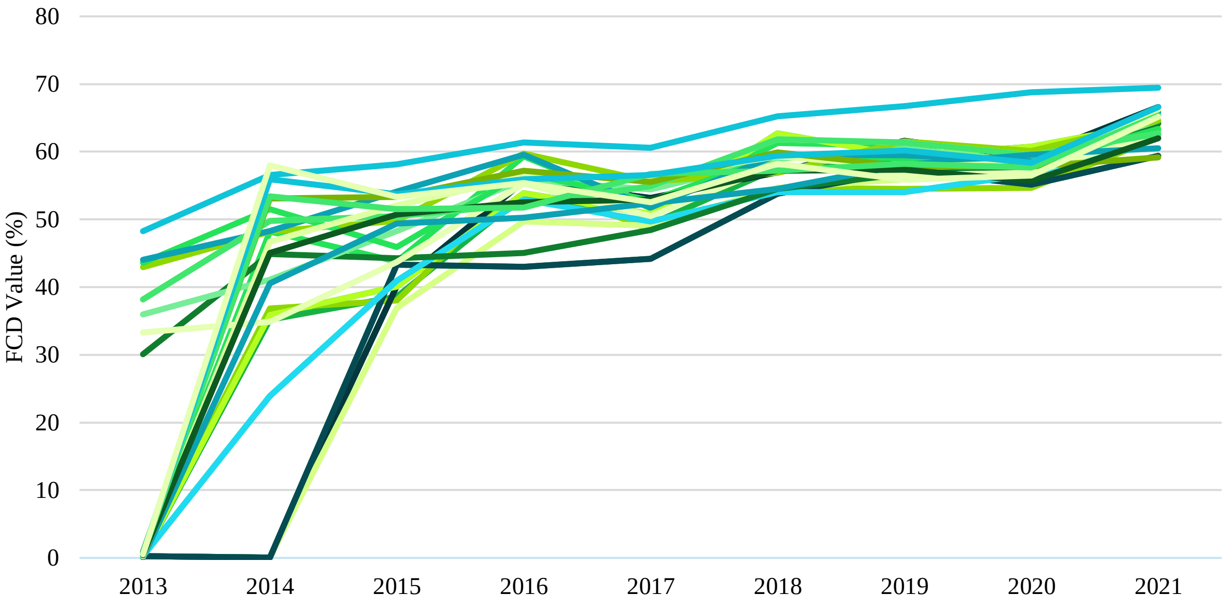


Figure 5 The trend of FCD values in 2013–2021 based on 50 random sampling points

At the study site, the reclamation of ex-mining land was achieved by planting *sengon* trees (*Paraserianthes sp*.). *Sengon* is one of the preferred tree species for industrial forest plantations and revegetation of mine reclamation land in Indonesia (Krisnawati et al. 2011; Zulkarnain et al. 2014). Based on the graph shown in Figure 5, there was a drastic increase in the FCD value in the first two years after the planting of *sengon*. This tree can grow rapidly, particularly in the first few years after planting (Krisnawati et al. 2011; Pratiwi et al. 2020). This is also supported by Zulkarnain et al. (2014), who found that in ex-mining land, the trunk circumference of *sengons* was four times higher than those planted in normal land. Thus, the FCD can also adequately monitor the growth of *sengon* trees. *Sengon* was selected as a revegetation plant in the reclamation area because of its capacity to increase soil fertility, low C/N ratio, wide canopy, and fertile and large ground cover vegetation (Zulkarnain et al. 2014).

Relationship Between Canopy Cover and FCD

The relationship between canopy cover and FCD was identified by statistical analysis using linear regression analysis with an assumption test of normality using the Kolmogorov-Smirnov test. The Kolmogorov-Smirnov test showed a statistical value of 0.086. This value is smaller than the critical value of 0.172, it is followed by a significant value of 0.2 which is greater than 0.05, with a confidence level of 95%. Based on this value, it can be concluded that the null hypothesis is accepted in this test. This indicates that the canopy cover and FCD data are normally distributed.

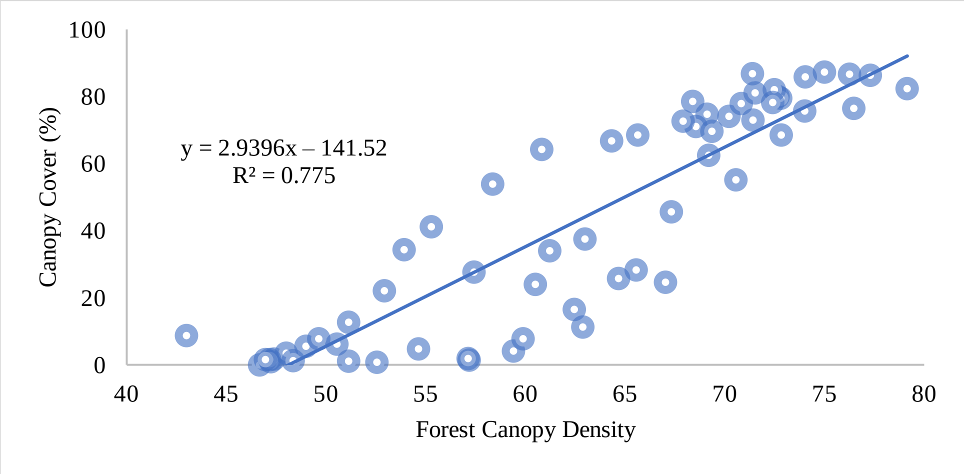
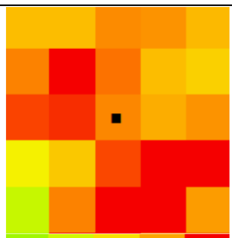
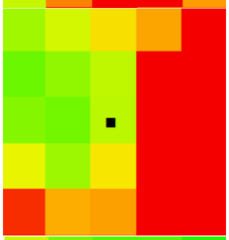
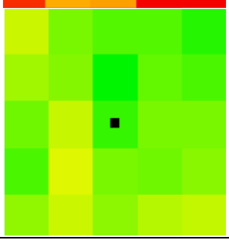


Figure 6 Linear regression between canopy covers and FCD

After the normality test, linear regression analysis was performed using 60 grid plots as ground-truthing sites to develop a prediction model for canopy cover based on FCD values. The results show a high correlation between canopy cover value (Y) and FCD (X) with a coefficient of determination of $R^2 = 0.775$ and with linear equation Y = 2.9396x – 141.52 (Figure 6). This analysis can be used to predict canopy cover for the reclamation of ex-mining land using the FCD value approach.

Table 2 The appearance of canopy cover in the field compare to FCD results

Canopy cover hemisperical photo	FCD maps	Canopy covers value (%)	FCD value
		8.7	43.7
		66.7	64.3
		82.27	79.2

In addition to the statistical calculation, Table 2 shows that the FCD model in this study has a strong relationship to represent the canopy cover, especially in the reclamation of the ex-mining area. To validate the accuracy of the FCD modelling in the study area, we evaluated the model by classifying the canopy density pixels based on the Indonesia Geospatial Agency (2014), which classifies the value of canopy cover into three classes of canopy density, namely a dense density class with a canopy cover percentage of > 70%, a medium density class with a canopy cover of 50–70%, and a sparse density class with a canopy cover percentage of < 50%, and then processed with a confusion matrix, as shown in Table 3.

Table 3 Confusion matrix of the FCD Model

FCD class	**Canopy cover class**			**Row total**	**User Accuracy (%)**
	Dense density	**Medium density**	**Sparse density**		
Dense density	16	1	1	18	88.89
Medium density	4	5	8	17	29.41
Sparse density	0	0	25	25	100,00
Column total	20	6	34	60	Overall
Producer accuracy (%)	80	83.33	73.53		Accuracy 76.67%

Table 3 shows that the overall accuracy of the FCD Model in the study area was 76.67%, indicating that the performance of the model showed a fairly good level of accuracy in describing the density of the canopy cover in the reclamation area of the study area. Previous research also showed great results of FCD accuracy in interpreting canopy cover in the field. Azizi et al. (2008) found the accuracy of the FCD in the Northern Iran Forest was 84.4%. Meanwhile the study of Godinho et al. (2016) in Alto Alentejano, Portugal found the accuracy was 81.3%. Similarly, Ashaari et al. (2018) also found the FCD accuracy was 81.27% in Bukit Baru Wildlife Sanctuary and recently Mondal et al. (2021) study in Sundarbans Biosphere Reserve, India found a 84.13% level of accuracy. Overall, the FCD model showed good performance for estimating canopy cover, both statistically and visually in the field.

Canopy Cover Estimation Based on FCD Values

Based on the Decree of the Minister of Energy and Mineral Resources No.1827K/30/MEM/2018 of 2018 concerning Guidelines for the Implementation of Good Mining Principles, the canopy cover criteria can be achieved when the canopy cover value reaches 80%. This means that a canopy cover value above 80 was considered a successful reclamation and a value below 80 was considered an unsuccessful reclamation. Therefore, the FCD values were then converted to a successful canopy cover value with an interval from 0 to 100.

Based on the previously obtained regression equation, the lowest FCD value was 48.14%, as shown by the regression line that intersects the x-axis in Figure 7. Meanwhile, the FCD value when fulfilling the canopy cover success criteria for land reclamation was 75.35. That is, the canopy cover level is said to be successful when the FCD value is above 75.35 and vice versa. Then, from these two intervals, a transformation of the FCD value is carried out, which is equivalent to the canopy cover, so that the relationship between the FCD value and the successful value of the canopy cover can be obtained, as shown in Figure 7.

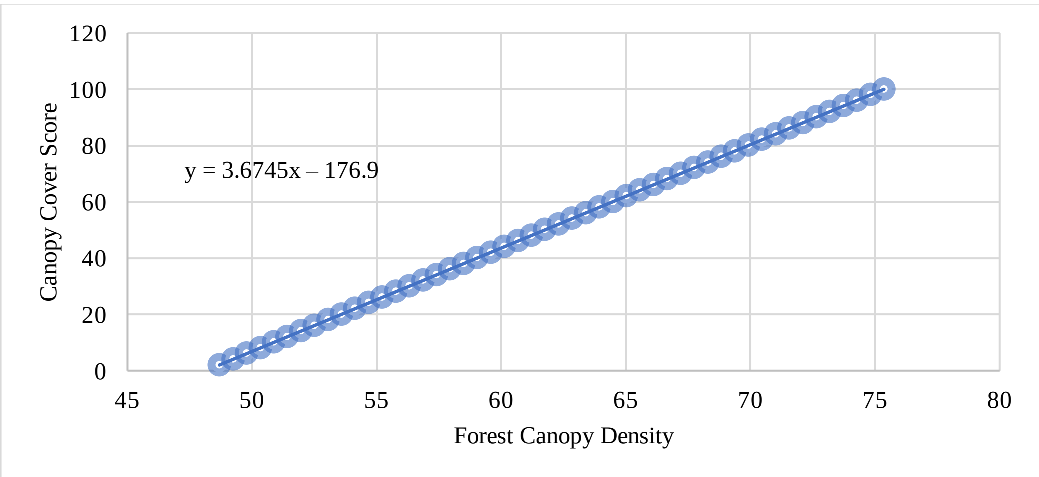


Figure 7 Canopy cover estimation based on FCD values

The correlation line between the FCD value and canopy cover value yields the equation Y = 3.6745x – 176.9 which as shown in Figure 7. By generating this equation, the FCD can be used to estimate the canopy cover value for the successful reclamation of ex-mining land. Until now, the assessment of the success of the reclamation of ex-mining land has not been measured, tends to be subjective, and requires more time and money. The FCD model can help mine inspectors determine the success of reclamation of a former mining land in a more effective, efficient, and measurable manner. In the process of monitoring canopy cover success on ex-mining reclaimed land, FCD modeling can also be the basis for the assessment team to identify canopy cover success scores remotely without having to survey the field. Canopy cover is one of the criteria for successful reclamation; therefore, the results of the FCD model assessment can determine the canopy cover assessment, which can determine the success score of reclamation of ex-mining land and can become government input in preparing future policies or regulations.

CONCLUSION

This study presents one of the few examples of canopy cover estimation by coupling field data (hemispherical photography) with remote sensing based on forest canopy density (FCD) modeling to assess and quantify the post-mining reclamation success rate. The spatiotemporal analysis of FCD values from one of the reclamation sites revealed a significant annual increase in canopy cover from 2013 to 2021. In addition, this study also found that the FCD could adequately monitor the growth rate of *Sengon* Trees in the reclamation area.

Regression analysis showed a strong relationship between the FCD value and vegetation canopy cover (R^2 = 0.775). This study also transformed the FCD values into a canopy cover success score, with the 75.35 of FCD values as a threshold for successful reclamation. Finally, this study clearly demonstrates that this approach can be applied to determine the success score of the reclamation of post-mining areas and make it possible to formulate and implement effective environmental assessment tools in the future. To conclude, this FCD model can be a powerful tool for mine inspectors/policymakers to implement more sustainable mining practices in Indonesia.

ACKNOWLEDGEMENT

This study was supported by Director General of Minerals and Coal, Ministry of Energy and Mineral Resources, Republic of Indonesia. The authors are grateful to the reviewers and the associate editor for comments and suggestions that have led to a significant improvement of this manuscript.

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