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RESEARCH ARTICLE

Comparison of All Return Cover Index (ARCI) and First Return Cover Index (FRCI) Methods for Mapping Percentage of Mangrove Canopy Cover using LiDAR Data

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Abstract. Indonesia has the largest mangrove forest in the world, around 3.3 million hectares or 19.5% of the entire mangrove's world population. Mangroves have many ecological and economic benefits and are also threatened by several conditions, such as a decrease in area, land, degradation, and the health of mangrove vegetation. One of the methods in maintaining the sustainability of mangrove ecosystems is mapping the biophysical aspects of vegetation, namely mapping the percentage of mangrove canopy cover using field measurements or remote sensing. This study aims to compare the accuracy of Light Detection and Ranging (LiDAR) data based on All Return Cover Index (ARCI) and First Return Cover Index (FRCI) algorithms in mapping the percentage of mangrove canopy cover and analyzing its spatial distribution. The study area is a mangrove forest in Ratai Bay Pesawaran Lampung. This forest is dominated by a dense and evenly distributed canopy cover class with an average value of 78.24% which was acquired using the hemispherical photography method. ARCI and FRCI methods are dominated by the dense and evenly distributed cover class with an average percent cover value of 85.39% and 89.78%, respectively. The accuracy of mapping the percentage of mangrove canopy cover using FRCI is higher than ARCI, with a maximum accuracy value of 93.08% and a standard error of 5.95%. That value shows that using LiDAR data with the FRCI method for mapping the percentage of mangrove canopy cover produces a high accuracy value.

1. Introduction

A mangrove is a tree or shrub that generally has a height exceeding one and a half meters and usually grows above mean sea level in the coastal zone of the sea or at the boundary of the estuary (Robertson & Alongi, 1992). Mangroves are one of the forests rich in ecological and economic benefits, of which there are 3.3 million hectares of mangrove forests in Indonesia (Rahadian et al., 2019). Globally, Indonesia is listed as a country with the largest mangrove forest in the world where around 19.5% of mangrove forests are in Indonesia (Bunting et al., 2018). Although it has much wealth, mangrove forests can also experience threats, such as decreased mangrove areas, which natural conditions or anthropological activities can cause. Hamilton & Casey (2016) stated that as much as 4.36 km^2 of mangrove forests in Indonesia experienced a decrease in area. This threat can undoubtedly disrupt the balance of ecosystems and biodiversity contained in mangrove forests, including wildlife habitat in it can also be eliminated. The condition of mangrove forests can be modeled using various methods, including mapping the percentage of mangrove canopy cover. In addition, mapping the percentage of mangrove canopy cover also plays an essential role in carbon stock estimation and simulation of wildfire estimation (Ma et al., 2017).

Information on mangrove canopy cover can be done through conventional mapping and remote sensing approaches. Conventional mapping of the percentage of mangrove canopy cover can use the hemispherical photography method, which requires a camera with good resolution (Korhonen et al., 2006). In addition, other simple methods, such as the intersect method, require much human labor. However, both methods still need to be improved in terms of time and relatively higher costs, and it is not easy to get good field measurements in mapping the percentage of canopy cover in the broader area. The selection of a more efficient method is an alternative, especially in mangrove forests, which have unique terrain characteristics that make the remote sensing approach more suitable for obtaining mangrove canopy cover information.

Remote sensing technology can be utilized to map the vegetation canopy cover percentage, especially using Light Detection and Ranging (LiDAR) data. The utilization of LiDAR data has been studied previously, as conducted by Ma et al. (2017), who compared methods in mapping the percentage of highland forest canopy cover between airborne LiDAR, aerial photographs, and satellite images. The results showed that using LiDAR based on the First Return Cover Index (FRCI) has a higher level of mapping accuracy than other remote sensing data. One of the advantages of LiDAR over other remote sensing data is that it is able to measure a geographical environment in three dimensions (3D). This is because LiDAR is able to record laser firing angle information so that the x, y, and z values of each return can be known, and LiDAR is also having accurate geometry or georeferencing accuracy. Another advantage of LiDAR is that the data can be acquired during the day or night as long as there is no thick fog or high humidity levels such as rain or snow, making LiDAR more effective that other passive optical imagery. The most useful characteristic of LiDAR not found in other sensors in vegetation studies in particular is that is its laser energy or pulse can penetrate canopy gaps and measure the structural elevation of the canopy and terrain along the recorded area (Dong & Chen, 2018).

The research was then tried to be applied by Azis (2019), which showed that LiDAR data based on the All Return Cover Index (ARCI) had better accuracy in mapping canopy cover in Central Kalimantan peat swamp forests. The utilization of LiDAR data in mapping the percentage of canopy cover based on ARCI and FRCI has yet to be consistent in forest vegetation in general. Therefore, it is necessary to apply the method in other vegetation forests, such as mangrove forests. Several studies related to the utilization of LiDAR data have reported that there are differences in accuracy between studies. As in the research of Wijaya et al. (2023), used airborne LiDAR to map mangrove vegetation structures in Ratai Bay, Lampung. Their canopy height model achieved an impressive accuracy of 82.3% to 88.6%, while the canopy cover percentage model ranged from 79.6% to 94.7%. Overall, their vegetation structure classification was 77% accurate. One of the other references in this study is research from Ma et al. (2017) systematically compared canopy cover estimations derived from LiDAR data, quick field measurements, aerial imagery, and satellite imagery using different algorithms. Although their study was not specific to mangroves, it provides valuable insights for applying similar methods to mangrove forests. Notably, their LiDAR-derived canopy cover estimates were marginally influenced by the estimation algorithms

However, one of the main issues is that the different objects mapped and the specifications of the LiDAR data used to make the mapping results obtained differ in accuracy. This research aims to develop LiDAR data utilization in mapping the percentage of ARCI and FRCI-based vegetation canopy cover applied in mangrove forests. Three objectives in this study: [1] analyze the distribution and data of the percentage of mangrove canopy cover from field measurements; [2] analyze the variation and spatial distribution of the percentage of ARCI and FRCI-based mangrove canopy cover using LiDAR data; and [3] calculating the accuracy of the results of mapping the percentage of ARCI and FRCI-based mangrove canopy cover using LiDAR data. In addition, in the context of research usefulness, this study is expected to provide knowledge to the broader community regarding a more accurate method of mapping the percentage of mangrove canopy cover to increase the effectiveness of monitoring or management of mangrove area management, especially for communities and managers in the local area.

2. Methods

Study Area

The study area is in Ratai Bay (Figure 1), administratively located in two villages: Padang Cermin Village and Sanggi Village, Padang Cermin District, Pesawaran Regency, Lampung Province. Geographically, the boundaries of the study area are 5°34'45"-5°36'54" North and 105°9'35"-105°10'48" East, with an area of 254.37 hectares. The selection of the research study area in Ratai Bay was based on several factors. First, the mangrove forest in this part of Ratai Bay is a natural mangrove forest and has not undergone much change.

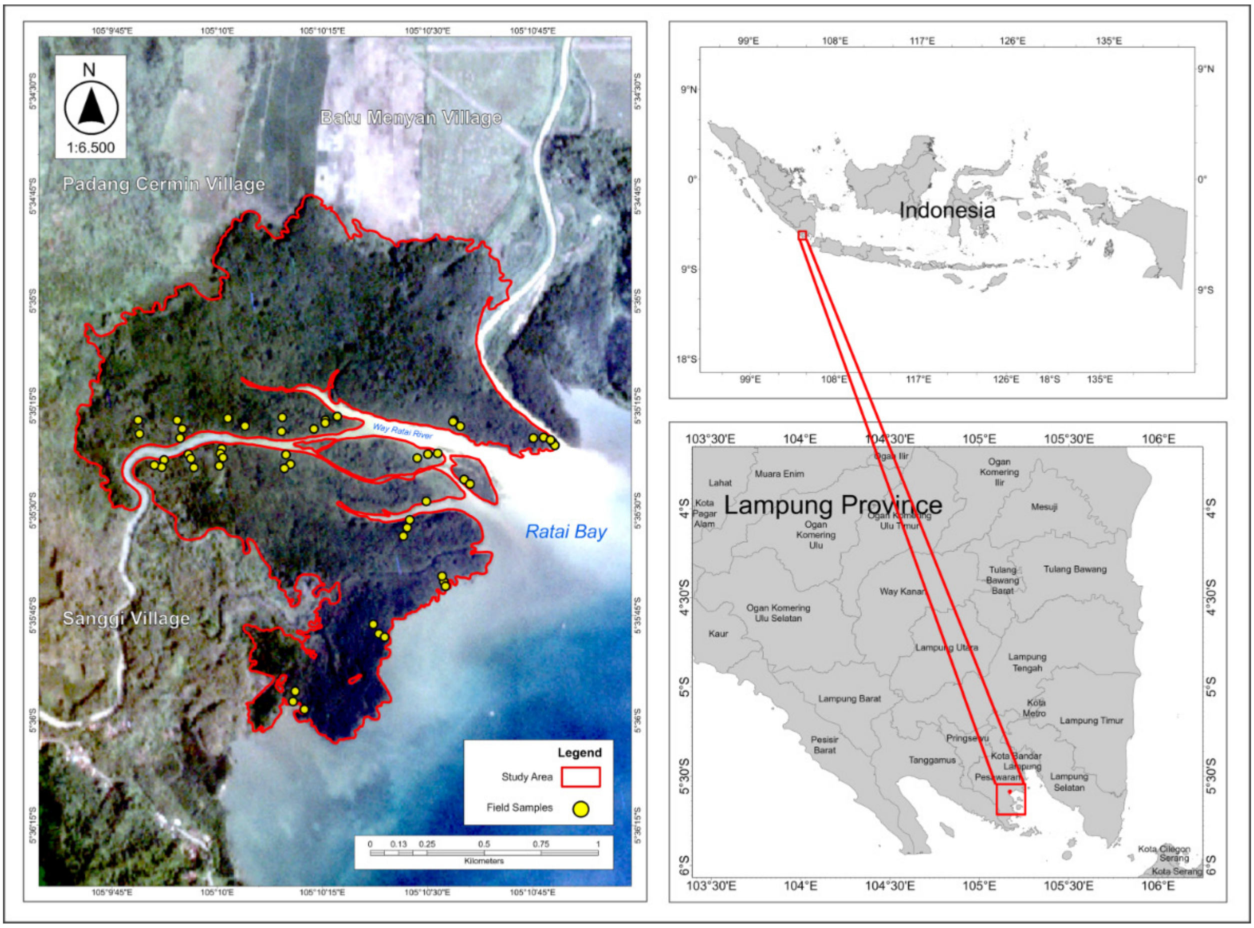

Figure 1. Study area and field sample distribution in Ratai Bay Mangrove Forest, Lampung, Indonesia

Second, the visible zonation of mangrove forests in some areas of Ratai Bay has the potential for mangrove biophysical measurements, such as the percentage of mangrove canopy cover, due to variations in height, canopy cover, and density. Based on direct observation in the field, the zonation of mangrove vegetation in Ratai Bay is homogeneously grouped. From sea to land the zoning layer starts from certain species such as *Sonneratia alba*, *Avicennia marina* to the center such as *Rhizophora apiculata* and *Rhizophora stylosa*. And there are also groups of *Nypa fruticans* that are quite colonized in some areas, especially around the Way Ratai river which is closer to non-mangrove vegetation. Third, the location has a varied mangrove ecosystem, especially at the species level, in which *Rhizophora apiculata* dominates. Other species that can be found at the site include *Acanthus ilicifolius, Acrostichum aureum, Avicennia marina, Ceriops tagal, Nypa fruticans, Rhizophora stylosa, Sonneratia alba, Xylocarpus granatum,* and *Xylocarpus mollucensis* (M, 2023).

Airborne LiDAR Datasets & LiDAR Pre-Processing

The data used in this study is airborne LiDAR to model the percentage of mangrove canopy cover. The data was obtained from the Geospatial Information Agency recorded on December 31, 2020, in Ratai Bay, Pesawaran, Lampung. The reason for using this LiDAR dataset is that it has a high laser point density of 20-30 points/m^2, which is optimal for mapping the biophysical parameters of mangrove vegetation. In addition, this airborne LiDAR data has a scan angle of 40-75˚ with a pulse rate of 1.0 MHz, which has the advantage of recording more comprehensive objects from various recording angles. The value of the mapping mission is multifaceted, primarily determined by key parameters such as flight altitude and overlap settings. Flight altitude directly impacts the spatial resolution and point density of the resulting data, higher altitudes cover larger areas per point but reduce point density, while lower altitudes yield higher density but cover smaller areas per point. Similarly, overlap settings, both side and front, influence data quality and processing efficiency. Higher overlaps ensure redundancy in data capture, enhancing accuracy in 3D reconstruction and feature extraction but also increasing data volume and processing time. Therefore, optimizing these parameters is essential to strike a balance between data quality, resolution, coverage area, and operational efficiency, ensuring the successful and cost-effective execution of mapping missions. The LiDAR data was acquired on December 31, 2020, at 19.00 UTC at low tide conditions so that the recorded mangrove vegetation objects were optimal for study.

Before being applied to the model, LiDAR data underwent pre-processing consisting of reclassification and rasterization processes. In this study, the LiDAR data exhibits a geometric accuracy of 4 centimeters. The correction for geometry leverages DGNSS (Differential Global Navigation Satellite System), ensuring precise spatial alignment. This reclassification process aims to improve and correct the point cloud class according to the recorded object. In this research, the required data classification is in the form of vegetation classes with a maximum height of 50 meters in types 3 (low vegetation), 4 (medium vegetation), and 5 (high vegetation). Therefore, objects other than these data types were removed, such as pulse data detected as buildings, water, or other noise. It is to facilitate LiDAR data processing in obtaining mangrove canopy cover information accurately. The rasterization process is essential because it is one of the effective ways to calculate canopy cover by dividing the study area into several small units of the same size through this rasterization process. We rasterized the LiDAR point clouds into 10x10 meters pixels in this case. The choice of a 10x10 meter pixel size for LiDAR data rasterization represents a trade-off between capturing relevant ecological detail and computational efficiency. This scale aligns well with typical field sampling plot sizes used in ecological studies, facilitating a direct comparison between LiDAR-derived canopy cover and ground measurements. Additionally, a 10x10 meter resolution reduces the visual impact of scan line artifacts present in smaller pixel sizes, leading to smoother visualizations and potentially mitigating autocorrelation issues in ecological modeling. Furthermore, a 10x10 meter pixel size helps balance the representation of canopy cover. Smaller pixels might overestimate cover due to capturing gaps within the canopy, while larger pixels might underestimate cover by smoothing over gaps entirely. This intermediate resolution provides a more accurate representation of the proportion of ground obscured by the tree canopy. This pixel size mimics the average size of the mangrove tree canopy in the study site.

Field Measurement

Field canopy cover data were collected for the accuracy assessment purpose of the resulting maps. In this study, we

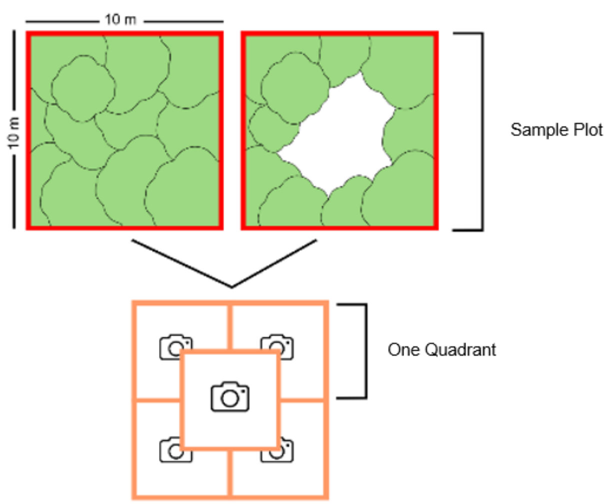

Figure 2. Field sample plot scheme.

took hemispherical photos vertically through a fisheye lens (180°) with a photo-taking height of about 1.5 meters from the ground. The results of the vertical shooting are further processed to calculate how much the percentage of canopy cover at each sample plot. The technique of taking hemisphere photos (Figure 2) considers several factors, namely identifying the distribution of canopy closure, determining the number of photos taken in each plot, determining the location of images in quadrants in the plot, the position of taking hemisphere photos, and finally taking hemisphere photos must meet valid requirements (Dharmawan, 2020).

The sample plot size of 10x10m was set up to consider the LiDAR raster pixel size. In this way, several point clouds on airborne LiDAR can represent the samples taken. In addition, this size also considers the optimum pixel size of the LiDAR data used to represent the condition of canopy cover in the field. The selection of a 10x10 meter size for both the field sample plot and the LiDAR data pixel size in this study reflects a thoughtful consideration of several factors. A crucial aspect is ensuring accurate overlay of field data with the high-precision LiDAR point cloud. Since GPS accuracy used for field plot positioning can be less precise, keeping the plot size smaller than the pixel size (10x10 meters) guarantees the entire plot falls within a single LiDAR pixel. This minimizes the potential influence of GPS errors during data integration. Furthermore, maintaining logistical efficiency in field data collection is important. Larger plot sizes would necessitate more time and resources for establishment and measurement. The chosen 10x10 meter plot size offers a practical balance, allowing for efficient field data collection while encompassing a representative area for analyzing canopy cover. Finally, the 10x10 meter pixel size likely emerged from a process of evaluating different resolutions during LiDAR data processing. Rasterization, the conversion of the raw point cloud into a gridded format, necessitates selecting a pixel size. Smaller pixel sizes (e.g., 1x1m or 2x2m) might capture the scan line pattern of the LiDAR data too precisely, leading to a “stripy” effect that can complicate visualization and analysis of canopy cover. Conversely, larger pixel sizes could smooth over crucial details in the canopy structure. Therefore, the 10x10 meter size represents a well-suited choice that minimizes noise introduced during rasterization while capturing an adequate area to represent the overall canopy cover for most ecological studies. It is important to note that the specific plot size might be flexible depending on the research question. Highly detailed studies of individual trees or specific canopy gaps might necessitate smaller plots with even higher GPS accuracy requirements. The features observed in the plot are the percentage of canopy cover using hemispherical photography, measurement of tree height, and observation of the dominance of existing mangrove species.

All Return Cover Index (ARCI) & First Return Cover Index (FRCI) Algorithm

Mapping the percentage of mangrove canopy cover using LiDAR can be done through an All Return Cover Index (ARCI) based approach (equation 1). This ARCI-based approach shows how much the ratio or comparison of all LiDAR returns intersects with the entire canopy recorded in the study area (Ma et al., 2017). The use of ARCI in mapping the percentage of canopy cover is based on its ability to extract more information, meaning that for shrubs or saplings, the percentage of canopy cover can also be calculated.

$$ARCI = \frac{\sum All\ canopy}{\sum All\ total} \tag{1}$$

$$FRCI = \frac{\sum First\ canopy + \sum Single\ canopy}{\sum First\ total + \sum Single\ total} \tag{2}$$

The First Return Cover Index (FRCI) for mapping the percentage of mangrove canopy cover only uses the first return in its information extraction (equation 2). FRCI shows the ratio or comparison value of the first return LiDAR or single return on a smaller canopy area or single canopy (Ma et al., 2017). Using the first return in the FRCI method emphasizes the assumption that intermediate returns and last returns provide little additional information about canopy cover estimation. FRCI considers all vegetation canopy cover as long as there are gaps in the area, including shrub mangroves. In contrast, ARCI only considers the peak canopy cover first recorded by LiDAR.

Based on Figure 3, when viewed from a horizontal perspective in the field, it is known that the ARCI method can cover all types of mangroves in the area ranging from large, medium, to small mangroves. However, this can be a weakness of this method because any object scanned by airborne LiDAR will have its information processed so that it can cause overestimation. The FRCI method only considers the first return of the entire return number from LiDAR, so the information obtained is a mangrove canopy that has been recorded and classified before.

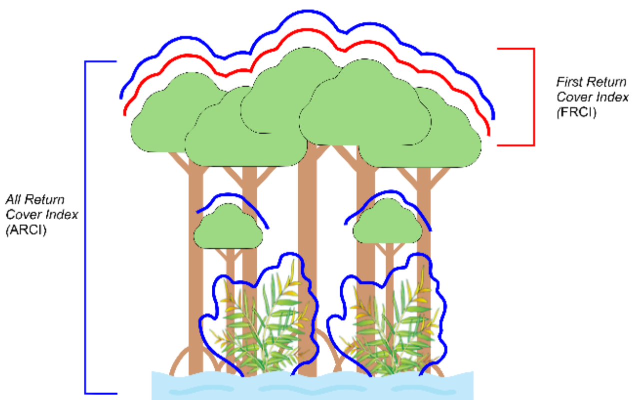

Figure 3. Comparison of ARCI and FRCI methods illustration from a horizontal point of view.

Accuracy Assessment of Percent Canopy Cover Estimation

This study was conducted to see the correlation between mangrove canopy cover values generated by LiDAR data and mangrove canopy cover measured in the field. First, the data obtained must go through several stages, including normality and regression tests, which are then selected as the best regression equation based on the coefficient of determination. The accuracy value is needed to determine the level of accuracy of the mangrove canopy cover map in describing how much percent of the actual canopy cover is in the field. This is done because of the limitations of the remote sensing approach itself. The accuracy test method used in measuring the accuracy value of the ARCI and FRCI estimation models is the Standard Error of Estimate (SEE). SEE is a value that shows the average distance of a population data to its regression line. It measures how precise the average value is obtained (Ghozali, 2011). In addition to statistical descriptions and presentation in tabular form, the accuracy assessment also be visualized in a 1: 1 plot. According to Kamal et al. (2020), a 1:1 plot can provide an explicit overview of the accuracy of the model built in terms of over and under-estimation. They can visualize the mapping accuracy between the LiDAR data used against the acquired field data.

3. Result and Discussion

Mangrove Percent Canopy Cover from Field Measurement

Field data acquisition in the mangrove forest of Ratai Bay Pesawaran was conducted in October 2022. The difference between LiDAR recording time and fieldwork is 1.8 years (from 2020 to December 2022). This time difference does not affect the condition of mangroves because, according to Verheyden et al. (2004), mangroves have a slow growth rate. In addition, no extreme natural disturbances or anthropogenic activities damaged the ecosystem. Except at some points, there were mangrove areas that experienced changes due to the lightning strikes, and there were several spots of mangrove planting areas. Data collection of mangrove percent canopy cover in the field using the hemispherical photography method with 52 samples based on purposive transect sampling. Hemispherical measurements using a fisheye lens contained in a 10x10 meter sample plot, along with plotting the coordinates of the sample point center using a Garmin 62s handheld GPS. Measurements were in the form of vertical shots of the canopy with a breast height of about 1.5 meters from the ground. Post-processing is then carried out for data acquired using a Gap Light Analyzer (Frazer et al., 1999) to get the percentage value of the canopy cover of the Ratai Bay mangrove forest.

Ratai Bay mangrove forest has a high average percentage of canopy cover. Based on the results of field measurements of the 52 sample points acquired, the high canopy cover class tends to dominate, namely with a canopy cover range of 70-100%, followed by a medium canopy cover class with a range of 35-70% and a low canopy cover class that tends to be rarely found (Figure 4). In addition, the average value of canopy cover of all samples acquired was 78.24%, which means that the Ratai Bay mangrove forest still has a reasonably high cover condition.

The high canopy cover class almost dominates all sample points, especially on the south side of the Ratai Bay mangrove forest, which has an average cover of >80%. The field's low canopy cover class is often found around the Way Ratai River. There are two categories in this low canopy cover class; the first is often found in mangroves that experience natural processes such as being hit by lightning so that the mangroves in the area are burned and cause the area to be slightly open. Secondly, on the east side or towards the bay, there are mangrove planting areas with an average tree age of <2 years, and the distance between mangroves is still tenuous, so it has low canopy cover and density.

Mangrove Percent Canopy Cover Estimation using ARCI and FRCI Methods

The airborne LiDAR data used previously must go through a pre-processing stage, namely the reclassification process, which aims to correct the return class so that the resulting model is more optimal and represents field conditions. Before modeling, a statistical analysis is needed to correlate the data acquired in the field with the model built from the LiDAR data.

Several statistical analysis tests were conducted in this study, including the normality, correlation, and regression test. The results of this regression test will be used to build a model of the percentage of mangrove canopy cover using the ARCI and FRCI algorithms. The normality test in this research is based on Kolmogorov-Smirnov with a sample size

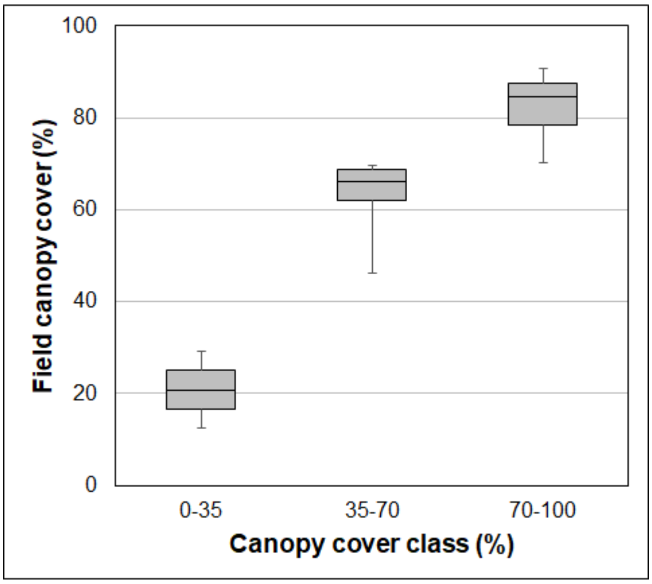

Figure 4. Field mangrove canopy cover class distribution

of 52 field data. According to Drezner & Turel (2011), data is said to be normally distributed if it has a significant value above 0.05, especially when using the Kolmogorov-Smirnov method. Based on the results of the normality test conducted, it is known that the data is normally distributed with a significance value of 0.268. Normally distributed field data is then classified into 2 (two) sample classes, namely model samples and validation samples. The division of this sample class aims for the following statistical analysis process. Field samples are then divided into 2 with a ratio of 7:3, or from 100% of the sample, there are 70% model samples, and 30% are validation samples with details of 36 samples as model samples and 16 other samples for accuracy testing. Correlation test results using the Pearson method show a strong correlation between field mangrove cover data and ARCI and FRCI-based LiDAR mangrove cover data. This is indicated by the Pearson Correlation value obtained in the range of 0.80-1.00. Although each strongly correlates with field data, the ARCI model has a slightly higher correlation value of 0.883 than the FRCI model, with a correlation value of 0.859.

The following statistical analysis was regression analysis. Regression is used to determine the causal relationship between one variable and another. In simple terms, regression analysis is a statistic that aims to visualize the statistical relationship between variables (Arkes, 2023). Visually, the scatter plot of the regression model in Figure 5 in this study has limitations. One of the limitations lies in the uneven distribution of data for some canopy cover classes, especially in the low cover class, and only some data for the medium canopy cover class. In this study, the ARCI method has a higher coefficient of determination of 0.7802 compared to FRCI, which only has a value of 0.7375 (Figure 5). Although different, both are still high for a model because if the R^2 value is closer to 1, the influence between variables is stronger. In other words, the canopy cover model using LiDAR can represent the condition of mangrove canopy cover in the field. Regarding the coefficient of determination, this study is under the research of Smith et al. (2009) and Hopkinson & Chasmer (2009), which respectively have R^2 values of 0.70 and 0.77 using the ARCI method. In addition, when compared to the research of Ma et al. (2017), this study has a higher R^2 value which only has a coefficient of determination of 0.33 in the ARCI method and 0.31 in the FRCI method.

Based on the results of canopy cover information obtained from LiDAR data extraction using the ARCI and FRCI methods, both highly correlate with the results observed through direct observation in the field. Visually, both maps show that the condition of the Ratai Bay mangrove forest is dominated by a dense and evenly distributed canopy cover class (Figure 6). This class of dense and evenly distributed canopy cover is almost spread throughout the mangrove forest area of Ratai Bay. This dense and evenly distributed canopy cover indicates the condition of the forest is still natural and has good vegetation health. The low anthropogenic activity in this Ratai Bay mangrove forest also supports this. In addition, the number of mangroves of the *Rhizophoraceae* family, which tends to be denser than other mangrove families, strengthens the results obtained from LiDAR data extraction in this study.

In addition to dense and evenly distributed canopy cover, there is another class based on the percentage canopy cover map above: the sparse and inconsistent canopy cover class. This sparse and inconsistent canopy cover class is usually found in mangrove forest areas affected by anthropogenic activities such as land conversion, logging, forest degradation, and other deforestation. In addition, sparse and inconsistent cover classes are also found at several points, especially mangrove areas damaged by natural degradation due to lightning strikes. The existence of these natural processes found during field data acquisition is closely related to the canopy cover percentage map obtained from LiDAR data. A burnt patch of *Ceriops tagal* due to a lightning strike was also detected on the percentage mangrove canopy cover map using ARCI and FRCI methods. This naturally degraded mangrove forest condition is mostly found on the western side of the Ratai Bay mangrove forest.

The percentage map of mangrove canopy cover obtained by both methods contains areas that do not have canopy cover information. It is due to the LiDAR data used in the area, especially on the northwest and north side of the Ratai Bay mangrove forest, which was not acquired during airborne LiDAR data collection. As a result, the mapped mangrove forest area only covers part of this study's targeted area of interest. Despite these shortcomings, the canopy cover percentage map obtained still represents the actual conditions in the field. Table 1 shows that the Ratai Bay mangrove forest is dominated by high canopy cover from field sampling data and models built using LiDAR data. This is supported based

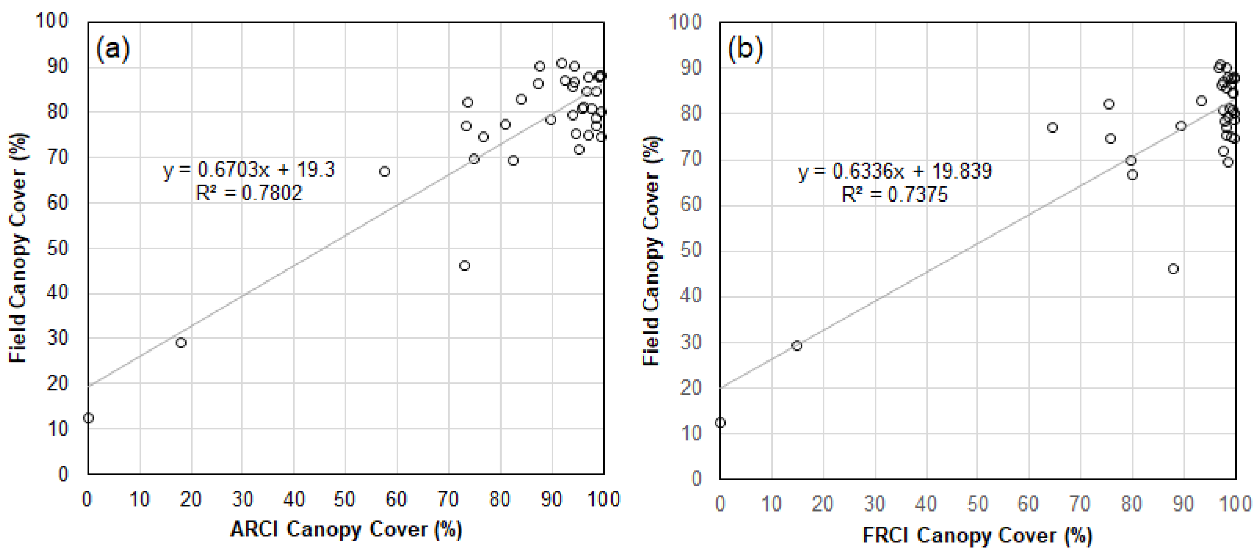

Figure 5. Regression test results of mangrove canopy cover percentage based on (a) ARCI and (b) FRCI algorithms.

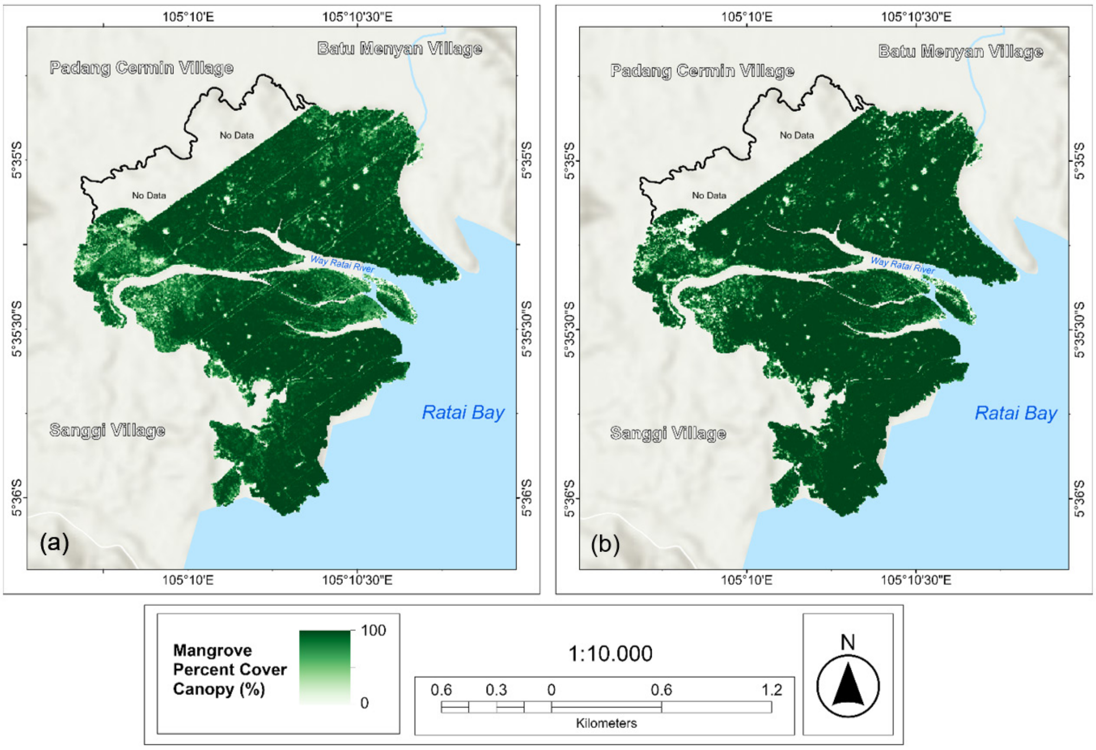

Figure 6. Canopy cover percentage map produced from (a) ARCI and (b) FRCI of the LiDAR data.

Table 1. Descriptive statistics of mangrove canopy cover percentage data

Percent Cover	n	Average (%)	Min (%)	Max (%)
Field	52	78.24	12.51	90.82
ARCI	52	85.39	0.00	100.00
FRCI	52	89.78	0.00	100.00

Source: Data Processing Result

Table 2. Accuracy assessment results of mangrove canopy cover percentage

Component	ARCI	FRCI
Standard Error (SE)	7,252	5,957
Max. Error	9,345	7,676
Min. Error	8,421	6,917
Max. Accuracy	91,578	93,082
Min. Accuracy	90,654	92,323

Source: Data Processing Result

on the mean and median values, where the field canopy cover has an average cover of 78.24%, while for ARCI and FRCI, it has an average of 85.39% and 89.78%, respectively. Although the mean and median are classified as one class, namely in the high canopy cover class, there are differences between the three based on the data distribution.

Accuracy Assessment of the Percent Canopy Cover Estimation

Statistical analysis is essential to see the mapping results' accuracy level. One of the objectives of this study is to determine which method has the best accuracy in mapping the percentage of mangrove canopy cover using LiDAR data between the ARCI and FRCI methods. Based on Table 2, the FRCI-based mangrove canopy cover percentage map has a minor standard error (SE) of 5.95 compared to ARCI, which has an error value of 7.25. The maximum error in mapping the percentage of mangrove canopy cover using FRCI-based LiDAR data has a smaller value of 7.67% compared to ARCI of 9.34%. The minor error or the slightest minimum error is also owned by the FRCI method, which is 6.91%.

In addition to considering some of the previous components, there is a maximum accuracy value of 93.08% using the FRCI method and the lowest accuracy at 90.65% using the ARCI method. Maximum accuracy and minimum accuracy themselves represent how much accuracy of the resulting map. The greater the value, the greater the accuracy of the map, which is the output of this research. Based on the results obtained, both ARCI and FRCI methods are pretty good at mapping the percentage of mangrove canopy cover because both have an accuracy rate above 90%. However, if we go back to one of the objectives of this research, the FRCI method is the best method compared to ARCI in mapping the percentage of mangrove canopy cover using LiDAR data. Prasetyo et al. (2018) conducted a study focused on canopy cover mangrove estimation using airborne LiDAR and

Landsat data. Their method, although not identical to ours, involved combining FRCI (Fractional Canopy Cover Index) with single-band Landsat imagery. The results from their study revealed a standard error value of 1.6%. However, it's essential to recognize that their estimates tended to be underestimates. In contrast, Ma et al. (2017) achieved canopy cover estimation with a significantly higher standard error value of 20%. Notably, their study did not specifically target mangroves. Our current research, situated within the mangrove ecosystem, demonstrates a remarkable improvement in accuracy, yielding a standard error value of just 5.9%. This advancement is attributed to our method's integration of LiDAR data. In summary, our study surpasses both Prasetyo et al.'s and Ma et al.'s accuracy levels, providing more reliable estimates for mangrove canopy cover. The combination of LiDAR data and our method has proven effective, even within the context of mangroves.

In our study, we investigated the differences between two commonly used canopy cover indices derived from LiDAR data: Single Echo Fractional Canopy Cover Index (SE FRCI) and All Returns Canopy Cover Index (ARCI). SE FRCI utilizes only the first return, representing the uppermost canopy layer, whereas ARCI incorporates all LiDAR returns, capturing information from various canopy layers. Consequently, ARCI tends to yield higher values due to its more comprehensive assessment of the canopy structure. However, SE FRCI may provide greater precision due to its reliance on a single return, potentially mitigating biases associated with subsequent echoes. This highlights a trade-off between comprehensiveness (ARCI) and precision (SE FRCI) that researchers should consider when interpreting these indices. Beyond the choice of index, several factors influence the overall accuracy of LiDAR-derived canopy cover assessments. These include GPS metric errors, where precise georeferencing is crucial, hemispherical sampling strategy to ensure data representativeness, point density, where higher density improves accuracy but increases processing demands, LiDAR footprint size, as larger footprints may obscure fine canopy details, and scan angle and line scan pattern, which can affect the distribution of LiDAR returns. In conclusion, our study underscores the importance of a comprehensive approach when analyzing canopy cover indices derived from LiDAR data. By carefully considering potential biases, error propagation, and the interplay of various LiDAR parameters, researchers can enhance the robustness and reliability of their analyses.

Mapping accuracy can also be evaluated using the 1:1 plot method by comparing the model and field conditions. It can be seen in Figure 7 that the conditions in the FRCI model tend to be overestimated, which shows that the plotted value is above the 1:1 line. Overestimation indicates that conditions are less suitable between LiDAR data and field data. Similar to the FRCI method, the 1:1 plot in the ARCI method also shows an overestimate, but some samples tend to underestimate it. Several factors can cause both overestimates and underestimates like this. One is the poor conditions when measuring or collecting canopy cover data using hemispherical photography in the field. Poor conditions can be light or photo exposure that tends to blur during measurement. Several factors can cause overestimates and underestimates like this. One is poor conditions when measuring or collecting canopy cover data using hemispherical photography in the field. These poor conditions include light or photo exposure that tends to blur during measurement. The canopy cover calculation software shows a denser or denser leaf structure, so the canopy cover tends to be higher than the actual condition, or the opposite can also occur. Uneven sample distribution also indicates why the data tend to underestimate or overestimate. The difficulty of finding evenly distributed sample areas or locations, especially for low canopy cover, is due to the difficult-to-access condition of the Ratai Bay mangrove forest. Accurate assessment of mangrove canopy cover is crucial for ecological studies and conservation efforts. LiDAR technology offers a powerful tool for this purpose, with various algorithms processing LiDAR data to estimate canopy cover. Two commonly used methods are the FRCI and the ARCI. FRCI demonstrates superior accuracy in modeling mangrove canopy cover compared to ARCI. This difference stems from how each method utilizes LiDAR data. LiDAR transmits light pulses and records the time for their return. The first return typically represents the highest point struck by the pulse, often the top of the mangrove canopy. FRCI capitalizes on this by solely considering the first return, effectively minimizing the influence of "noise" from objects below the canopy, such as understory vegetation and ground. In contrast, ARCI incorporates all return signals, including reflections from branches, shrubs, and even the ground. This inclusion, particularly in dense mangrove forests, can lead to an overestimation of canopy cover due to the additional points from lower vegetation layers. Therefore, by focusing on the first return and reducing the impact of these external factors, FRCI provides a more accurate representation of true mangrove canopy cover.

4. Conclusion

This study concluded that the results of field measurements in the form of hemispherical photography were dominated by the class of dense and evenly distributed canopy cover, which

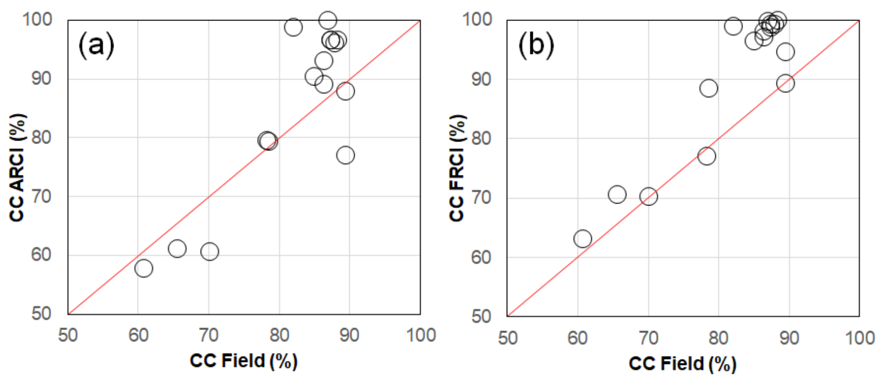

Figure 7. Plot 1:1 of mangrove canopy cover percentage (a) ARCI; (b) FRCI.

was almost found at all sample points, especially on the south side of the Ratai Bay mangrove forest with an average cover value of 78.24%. Other classes, such as sparse and inconsistent canopy cover, were found on the west side of the mangrove forest, which experienced a natural degradation process due to lightning strikes, leaving the area open. Mapping the percentage of mangrove canopy cover of Ratai Bay using LiDAR data can be done through two approaches, namely ARCI and FRCI based. Both ARCI and FRCI-based mangrove canopy cover percentage maps are dominated by tight and evenly distributed canopy cover classes with an average value of 85.39% and 89.78%, respectively. The dense and evenly distributed canopy cover class is found on the north and south sides of the Ratai Bay mangrove forest, which is dominated by mangroves of the Rhizophoraceae family. The FRCI method applied in mapping the percentage of mangrove canopy cover of Ratai Bay has a better accuracy value than the ARCI method, with a maximum accuracy value of 93.08% and a standard error of only 5.95%. At the same time, the ARCI method has a maximum accuracy value of 91.57% and a standard error value of 7.25%. Accuracy of mapping the percentage of mangrove canopy cover based on ARCI and FRCI when viewed from a 1: 1 plot shows a tendency to overestimate. However, a similar approach to this study can be applied to mangrove forests with different environmental settings, species composition, and zonation to verify the findings of this study.

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