The Use of Remote Sensing Data to Estimate Land Area with Forest Vegetation Cover in the Context of Selected Forest Definitions

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Abstract: (1) Background: Like many other countries, Poland is obliged to report forest area to the Climate Convention (UNFCCC Kyoto Protocol) and the Food and Agriculture Organization of the United Nations (FAO/UN). Differences between national and international forest definitions lead to differences between actual and reported forest area. Remote sensing is a useful tool for estimating forest area for reporting purposes. One of the most important parts of the estimation is the choice of a basal area to calculate the percentage of vegetation cover. (2) Methods: Height, crown projection area, and minimum complex area were used to classify the area with forest vegetation. Percentage canopy cover was determined using three different methods based on segmentation polygons, triangular grid and canopy height model pixels. The accuracy of the above methods was verified by manual vectorization performed on a selected set of test plots in the Milicz study area according to the international definitions. The differences were examined using three statistical metrics. (3) Conclusions: This paper compares for the first time methods for determining the area for which canopy cover is calculated (using data from (ALS) and discusses the differences between them in the context of accuracy (the correspondence between the results and the reference data) and the complexity of the process (time and effort required to perform the analysis). This is important in the context of reporting, estimating carbon stocks and biodiversity to mitigate the effects of climate change. Method 2 proved to be the most accurate method, Method 1 was found to be the worst option. Accuracy was better in the case of the Kyoto Protocol definition.

Keywords: lidar; forest vegetation; remote sensing; forest definition; reporting

1. Background

Throughout the world there are a number of forest definitions. Some of these are formulated in national law and apply only to the forests of that state, while others are international. The differences in forest definitions arise from the different characteristics of forest vegetation around the world and the different forms of forest management [1]. In addition, the differences in forest area under different definitions are influenced by the geometric characteristics of trees [2–6]. There are also some economic and political reasons why different countries consider certain areas to be forests [7].

One consequence of using different definitions is the discrepancy in area statistics between individual countries or continents. Depending on the data and methodology, the global rainforest area ranges from 1090 to 1220 million hectares, in Africa from 185 to 215 million hectares, in Asia from 235 to 275 million hectares, and in South America from 670 to 730 million hectares (Table 1) [8]. The difference in estimated forest area for 19 European countries was 13% [2], and the difference in area affected by deforestation in Indonesia during 2000–2009 was 27% [6]. These reported differences were the result of different definitions and methods used. The problem is exacerbated when a country

is required to report its forest area to an international organization and forest definitions differ significantly.

Table 1. Tropical forest area (10^3 ha) estimates of Central and West Africa Central America, Caribbean and South America from TREES project, FAO FRA 90 (FAO, 1993) and IUCN according to Mayeux (et al., 1998) [8].

	Land Area	Evergreen and Tropical Rain Forest	Tropical Rain Forest	Wet, Moist and Mountain Forest	Closed Broadleaved Forest	Closed Forest
Central Africa	398,320	183,967	78,821	202,456	158,300	185,802
West Africa	203,803	17,859	3231	52,223	15,569	13,470
Total Africa	602,123	201,826	82,052	254,679	173,869	199,273
Central America	50,977	18,029	11,957	21,525	17,499	22,649
Caribbean-Mexico	202,934	32,858	267	746,763	10,130	54,321
South America	1,002,297	652,772	438,932	715,509	637,050	615,605

For example, Poland, like many other countries, is required to report forest area for the Climate Convention (Kyoto Protocol) and the Food and Agriculture Organization of the United Nations (FAO/UN). Reporting of forest area in Poland is based on data published in the statistical yearbooks "Forestry" and "Environmental Protection" of the Central Statistical Office. Details of the definition of forest area formulated for Poland in the Forest Act (Act on Forests, 1991), FAO/UN [9–11] and the Kyoto Protocol [12] are presented in Table 2 [13–16].

Table 2. Criteria for delimiting forest areas.

Variables	Law on Forests—Poland	FAO	Kyoto Protocol
Minimum area (ha)	0.1	0.5	0.1
Minimum height (m)	-	5	2
Minimum crown coverage (%)	-	10	10
Width of the forest complex (m)	-	-	10
Land intended for renovation	yes	yes	yes
Land intended for natural succession	yes	yes	yes
Hunting plots	yes	yes	yes/no
Christmas tree plantations	yes	yes	yes
Post-agricultural land with secondary succession	no	yes	yes
Land related to forest management	yes	yes	no
Orchards and urban greenery	no	no	yes

The definition of forest in the 1991 Forestry Act (in Poland) does not require canopy cover or height. However, forest plantations established in state forests are considered successful if crown closure is at least 50% in the fifth year after regeneration. Conversion of agricultural land to forest land (under the Rural Development Program) occurs when the suitability determined on the basis of land cover is 50% for land with natural succession or 70% for artificial afforestation. However, there is still no minimum canopy cover and height required to recognize an area with forest vegetation as forests. Areas with or without forest vegetation may be also excluded or included in the forest area due to their land use. Moreover, there are many such rules that result in the forest area, which varies according

to the definition used [13–16]. Ultimately, different forest areas are reported even for a single country.

Since the methods used to define a forest area often vary from country to country, it is important to develop a methodology that is as homogeneous/utilitarian as possible. In line with Neef et al. [17], this allows a trade-off between reporting reliability, ecosystem characteristics and social and economic needs.

The simplest methods for estimating forest areas include manual vectorization [18] and NDVI index-based analysis, including change detection analysis performed on multiple images [19]. Statistical estimation methods based on data from regularly distributed sample plots are an important means of estimating forest area in sparsely populated countries with a very high proportion of forested areas, where conventional in-situ inventory in each forest sub-area is simply impossible (e.g., Canada, Russia) [20–26].

Aerial and satellite imagery have been successfully used since the early 2000s to estimate the area of forested areas with an accuracy of 80% for forest areas [20–22,27–32], 95% for secondary forests [18,19,33–35], and 75% for trees in agricultural areas [36]. Other sophisticated image-based methods include object segmentation and supervised classification [30,35], but few of them consider the geometric features of forest vegetation-height [32,34] and canopy [34] mentioned in the international forest definitions with an overall accuracy of 95%. However, their fractional values (1 m, 2–20% cover) do not correspond to the values given in the international forest definitions (2–5 m, 10%). Although image-based remote sensing technology is very useful for forest area estimation, its full potential has not yet been discovered and there are still many unsolved problems.

Airborne laser scanning data (ALS) provide information on elevation, which is an important variable in forest definition. Currently, up-to-date ALS data are available in many countries worldwide (in Poland within the ISOK project—IT system of Country Shield) and are widely used for remote sensing analysis. Since, at least in Europe, there is already a nearly homogeneous ALS database covering almost all of Europe, it is important to develop automatic methods based specifically on the data from ALS. The use of ALS data makes it possible to achieve or improve the results of forest area estimations [22,26,32,34–37]. Single tree extraction based on airborne laser scanning data (ALS) has been discussed in numerous publications [38–47]. It allows the creation of a vector layer of polygons representing individual trees with the projection area and height. The collection of individual trees allowed the analysis of species and health status at the individual tree level [48]. However, ALS data has its disadvantages as well, e.g., ineffective during heavy rain or low hanging clouds, at high sun angles and reflections, low operating altitude of between 500–2000 m and a decreased ability penetrating very dense/thick forests.

Land use is an important factor responsible for differences in official forest area statistics [5]. However, remote sensing methods can only classify areas in terms of their cover. Unfortunately, it is not possible to determine the land use category according to BDOT (Spatial Object Database) or other national land use databases. There are areas of forest vegetation that are not forest land by various definitions (e.g., post-agricultural areas with secondary succession, swamps, etc.), and forest land that is permanently or temporarily not forested (e.g., areas with intensive forest management—clearcuts, wind damaged or burned areas, etc.). Species composition may also be an important factor, as some countries have plantations of industrial crops that may (or may not) be considered forests for political (rather than ecological) reasons [4,6].

There is currently no consensus on how to determine the area for which tree canopy cover should be calculated [49]. Individual authors have investigated the accuracy of different methods, but none of them have attempted to compare these methods. Eysn et al. [50–52] and Sackov and Kardos [53] used a triangulation-based method that calculated the fraction of tree canopy cover for the area under the canopy of three adjacent trees and the intervening tree. They achieved an accuracy of 96–98.4% and 93%, respectively. Straub et al. [54] used a grid of squares with a defined mesh area for this purpose and achieved 97.7% accuracy. Wang et al. [27–29] calculated the percentage of pixels that were above a

certain threshold using the Canopy Height Model (CHM) in a grid with a defined mesh area. A detailed description of the methods can be found in the "Methods" chapter.

An important part of the remote sensing analysis related to forest area estimation is the accuracy assessment based on inventory data, which may differ significantly due to many factors, e.g., the number and distribution of sample plots, measurement methodology [3,54], or simply due to outdated records in existing databases [13–16,55]. When statistics are used in inventory procedures, sampling and inference methods can also affect estimation results [8]. This approach to collecting reference data is particularly useful in sparsely populated countries with a very high proportion of forest (e.g., Canada, Russia), where the forest area is too large to conduct a full in-situ field inventory. In Poland, the area covered with trees is classified as forest, rather than woodland, when preparing management plans according to the Forest Act (Poland, 1991), and it is based on a field survey of individual stands. Thus, in the case of the reference data, each stand was visited by a forest expert and many different characteristics were estimated or measured in the field (Table 2).

In this paper, we focus on the use of airborne laser scanning data and the estimation of three variables that determine the presence of forest vegetation in the international forest definitions: Elevation, Crown Projection Area and Forest Complex Area, which have not been fully considered in previous works, i.e., [32–34].

The objectives of the study were: (i) to determine the most accurate method, (ii) to calculate the differences between the analyzed methods according to the forest definitions used, (iii) to determine the most effective method in terms of accuracy (the agreement between the results and the reference data) and the complexity of the process (time and effort required to perform the analysis).

This paper compares for the first time methods for determining the area for which canopy cover is calculated (using data from ALS) and discusses the differences between them in terms of accuracy (the correspondence between the results and the reference data) and the complexity of the process (time and effort required to perform the analysis). The area with forest vegetation is a starting point for assessing the forest area according to international definitions, taking into account land use and its future evolution, even without current forest vegetation. This in turn is important in the context of reporting, estimating carbon stocks and biodiversity to mitigate the effects of climate.

2. Methodology

2.1. Study Site

The study was conducted in the Milicz Forest District (Figure 1), which has a high variability in forest habitat characteristics (Table 3). Forest habitat type is a basic unit in forest habitat classification, which includes all forest areas with similar habitat conditions that have similar production possibilities. The volume of a stand is usually limited to roundwood, measured in cubic meters [56].

The complex is primarily related to the oak–hornbeam habitat. It stretches from Młyńska Woda—a tributary of the Barycz River, to Żmigród, forming a line that is approximately 28 km long and up to 8 km wide. Mixed complexes were formed there, in which pine, sometimes spruce, oaks, hornbeams, beeches, birches, as well as ash trees, mainly high and low oak-hornbeam forests and beech trees grow. It is difficult to navigate in these stands due to the dense undergrowth of mountain ash, bird cherry, buckthorn and similar species. The cleanliness of the environment is evidenced by the presence of, among others of Icelandic lung lichen. In some areas, fertile beech forests developed in fertile habitats have survived. Their particularly beautiful fragment near Postolin has been protected since 1962 as a forest and landscape reserve called "Joan's Hill" with an area of 24.6 ha) common beech on the eastern border of this species range. There is also a mixture of oak, ash, pine and spruce. The highest natural value is characterized by the fertile lowland beech and a fragment of acidic lowland beech forest, the liverwort and the eagle-owl fern [56].

Table 3. Characteristics of stands in the research area.

Scheme	Habitat	Species	Age	Volume
Milicz Forest Department	Fresh coniferous—19.2% (1572.3 ha) Fresh mixed coniferous—26.8% (2198.1 ha) Wet mixed coniferous—5.1% (413.9 ha) Fresh deciduous—13.5% (1105.1 ha) Fresh mixed deciduous—13.1% (1072.2 ha) Wet mixed deciduous—4.5% (369.4 ha) Wet deciduous—2.6% (216.5 ha)	Pine—74.9% (1,973,262.2 ha) Oak—10.6% (279,260.1 ha) Beech—5.8% (152,802.7 ha) Birch—2% (52,690.6 ha) Alder—4.7% (2476.5 ha) Other—2% (52,690.6 ha)	0–20—12% (316,143.5 ha) 20–40—15% (395,179.4 ha) 40–60—29.6% (779,820.6 ha) 60–80—13.6% (358,295.9 ha) 80–100—12.7% (334,585.2 ha) >100—15.6% (410,986.5 ha)	Beech—300 m^3/ha Pine—298 m^3/ha Alder—285 m^3/ha Oak = 275 m^3/ha

Many hiking trails run through the Milickie Forests. Wandering them, however, requires a good map, which becomes necessary with the massive presence of mushroom pickers. The red trail from Żmigród through Sułów to Milicz-Karłów, almost exclusively through the forest, is of great importance. Early autumn is an attractive time of the year, when the beautiful colors of the landscapes are given by the clusters of beech trees. The forests of Milicz are distinguished by the great biodiversity of forest animals. You can meet deer, roe deer, fallow deer, wild boar and many other forest inhabitants [56].

2.2. Remotely Sensed Data

Airborne laser scanning (ALS) data were collected in August 2015 using a Riegl LMSQ680i laser scanning system with a pulse frequency of 360 kHz, resulting in point clouds with an average of 10 pulses/m^2. The mean flight altitude was 550 m and the field of view of the scanning system was 60 degrees. Together with the point clouds, the data provider created a digital surface model (DSM) and a digital terrain model (DTM) with a spatial resolution of 0.5 m using TerraSolid software. This DTM was used to normalize all yields from the raw point clouds [57].

Polygon layers representing the crowns of individual trees (with a given area and height) were used for the analyses and were created for the REMBIOFOR project "Remote sensing for determining wood biomass and carbon stocks in forests", which was conducted at the Forest Research Institute from 2014–2018. The segmentation method [58] used the CHM and adaptive kernel windows in relation to tree height. Taller trees were smoothed with a larger kernel window and shorter trees were smoothed with smaller kernel windows. In total, three groups of trees were defined with respect to height for coniferous and deciduous tree species. Analysis of the results shows that the method works well for dominant trees in the sample and provides a good accuracy (about 80%) in correctly detecting trees. When segmentation errors occurred, they did not significantly affect the results, as tree canopy cover was the target and not the exact number of trees. The layer of polygons representing individual tree crowns from segmentation is provided with information on their height and crown projection area in the table of attributes.
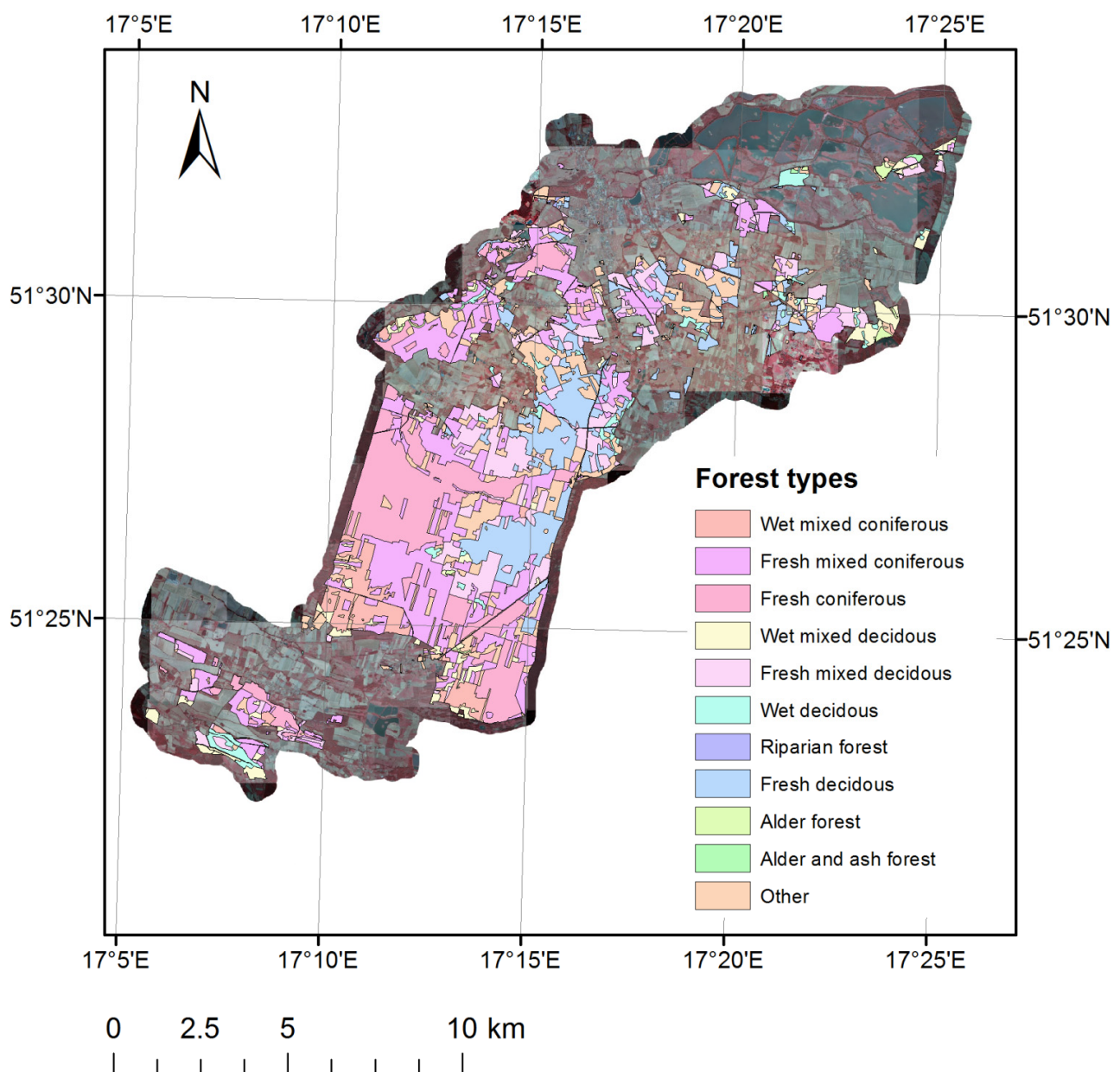
Figure 1. The area of investigation (Forest types and orthophotomap).

2.3. Methodology in General

A diagram of the analyses is presented in Figure 2.

Geometric parameters of vegetation (height, area of crown projection, minimum complex area) were used to classify the area with forest vegetation. Land use information was not used. The area with forest vegetation was calculated separately for three methods according to the FAO/UN and Kyoto Protocol definition. The results were compared to the reference data and the differences were assessed using statistical metrics.
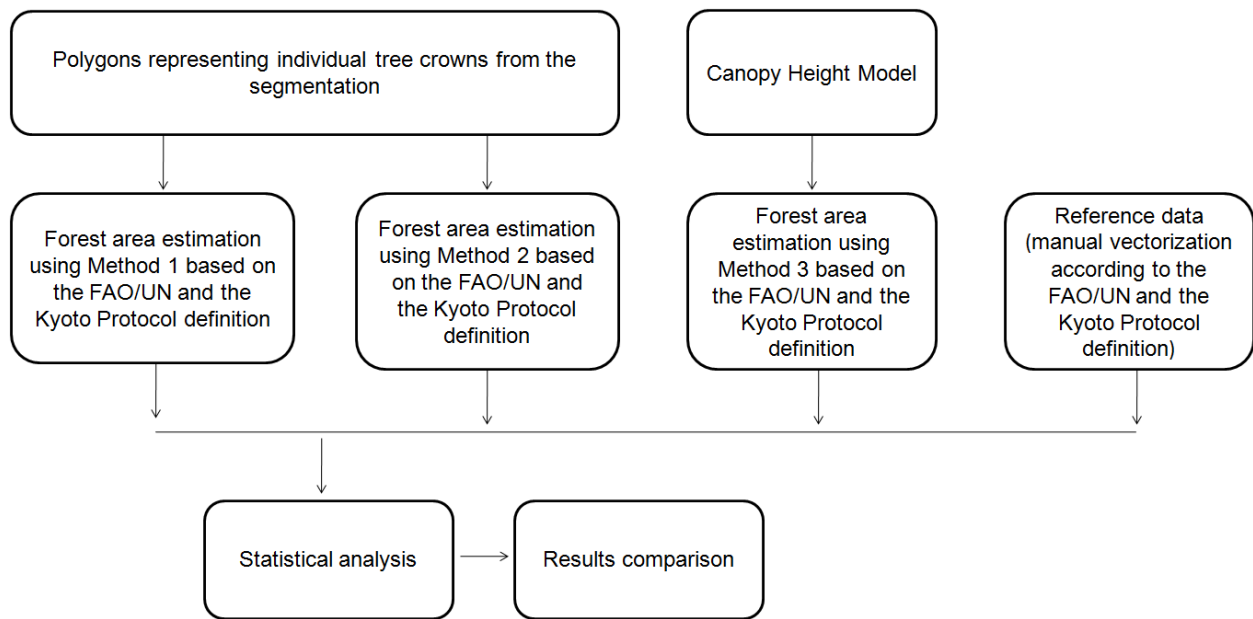
Figure 2. The scheme of the analysis.

2.4. Methods for Determining the Canopy Coverfrom ALS Data

For the FAO/UN definition, percentage cover was determined using three different methods, which are described below.

The first method is based on a triangular grid such that each point representing a tree is the vertex of one of the triangles. Such a triangular grid can be created using the Delauney triangulation method. Irregular polygons created during a segmentation process were used to represent the individual trees of 5 m and higher. The areas for which percent cover is calculated ("Convex Hull") were created based on groups of trees (three each) defined by the vertices of the triangles, as shown below. This method was used in the analysis and abbreviated as Method 1 [50–53] (Figure 3).
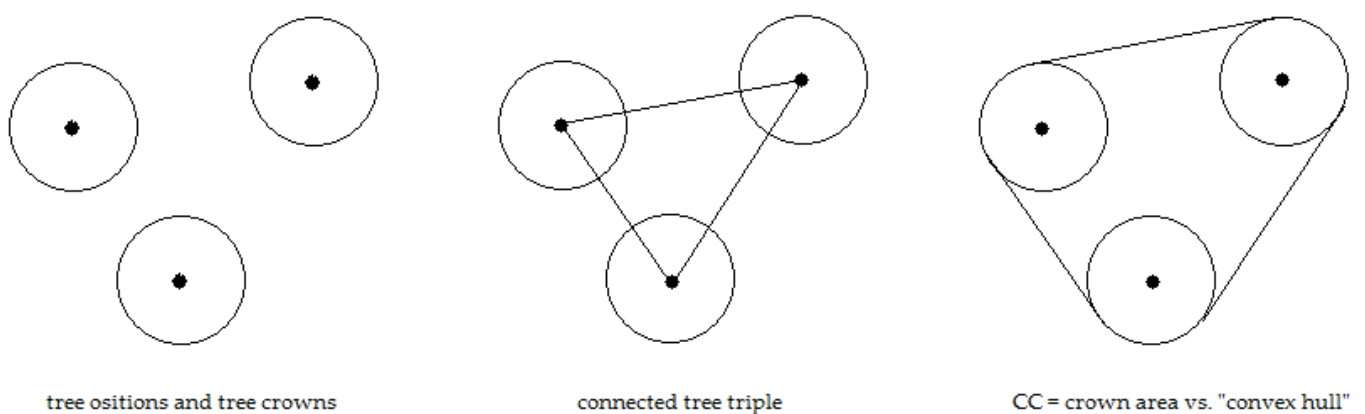

Figure 3. Area for which the percentage cover is calculated: Method 1 [50–53].

The second method uses only the polygons representing individual tree crowns from the segmentation [54]. This method was abbreviated as Method 2 (Figure 4).
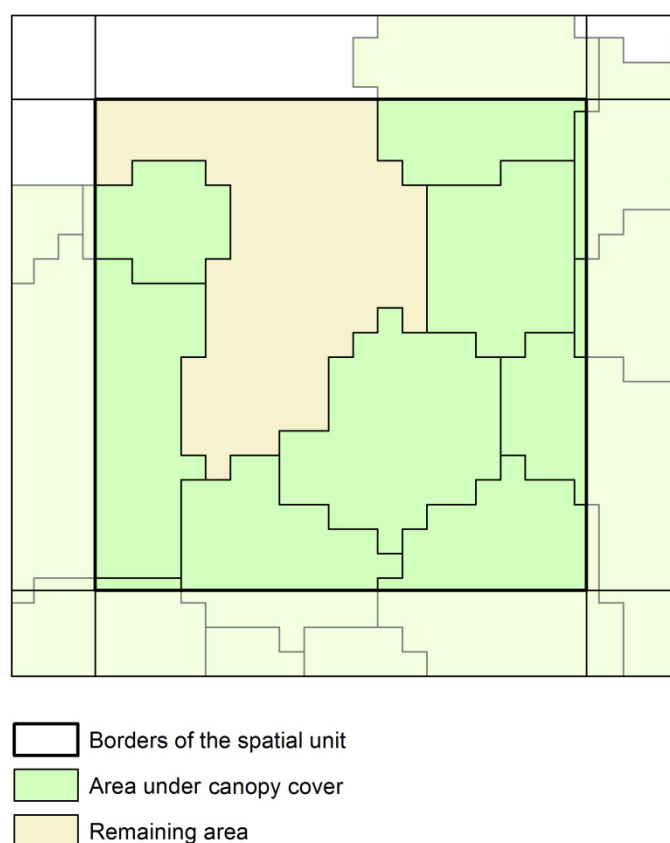
Figure 4. Area for which the percentage cover is calculated: Method 2 [54].

The third method uses only the pixels representing forest vegetation with a height of at least 5 m on Canopy Height Model [27–29]. This method was abbreviated as Method 3 (Figure 5).

For the Kyoto Protocol definition, the criteria were a minimum height of 2 m, 10% for percentage cover, and 0.1 ha for the area of a forest complex. For the Kyoto Protocol definition, percent cover was calculated in the same way as for the FAO/UN definition described above.

At the final stage, the results consist of 6 levels (3 methods times 2 definitions) representing the area covered by forest vegetation for the Milicz study area described in the "Study Area" section. The three methods were summarized in Table 4.

2.5. The Reference Data

The accuracy of the above methods was verified by manual vectorization performed on a selected set of 270 test plots (10 × 10 m^2) and 30 test plots (30 × 30 m^2) in the Milicz study area according to the definition formulated by FAO/UN and the Kyoto Protocol.

The centre of the test plots was selected from the circular test plots established during the field inventory. The data from the study area—tree height, canopy length and width measured in two directions—helped in vectorization based on the tree canopy height model and orthophotomap. Crown length and width were measured using a simple tape measure. Tree height was measured using the Vertex IV device (Haglof Sweden AB, Langsele, Sweden). Each test plot was classified as forest or no forest based on the height and canopy criteria.

An example of the vectorization results is shown in Figure 6. The results can be found in Table 3.
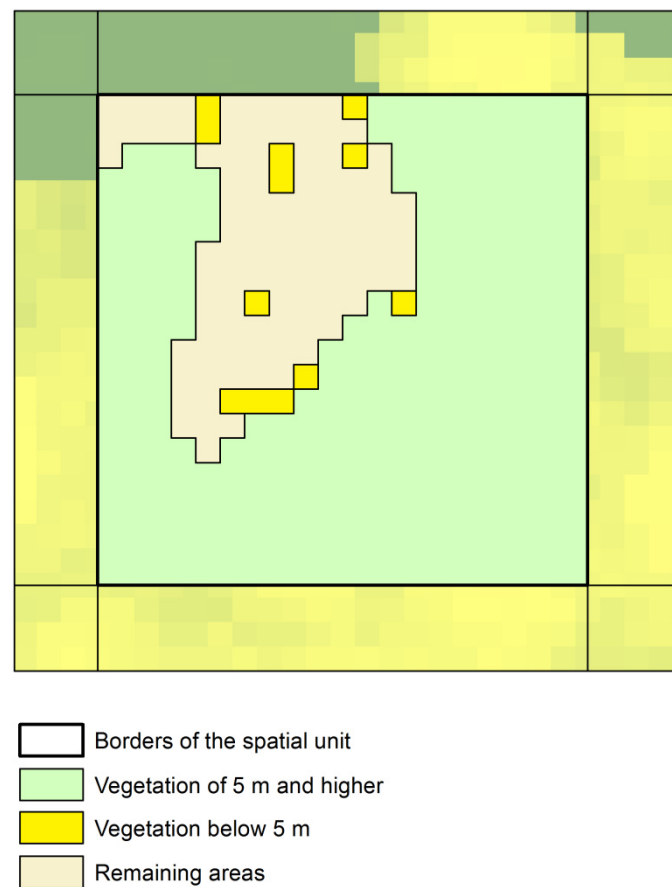
Borders of the spatial unit

Vegetation of 5 m and higher

Vegetation below 5 m

Remaining areas

Figure 5. Area for which the percentage cover is calculated: Method 3 [27–29].

Table 4. The summary of the three methods.

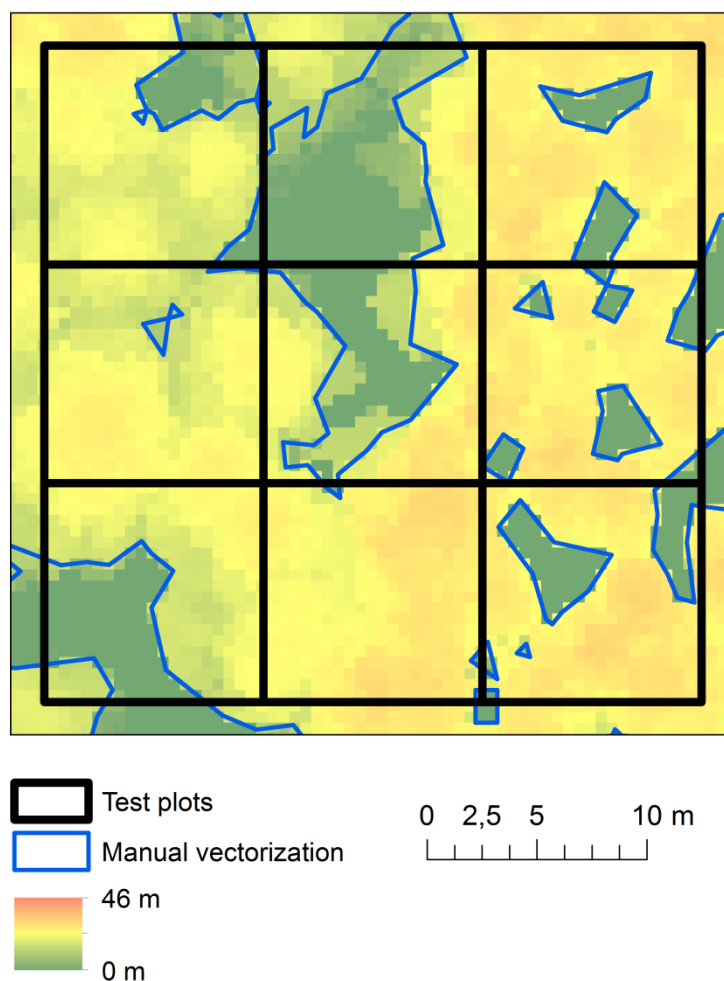| Method	Reference	Description
Method 1	Eysn et al., 2010, 2011, 2012 Sakcov and Kardos, 2014 [50–53]	The first method is based on a triangular grid such that each point representing a tree is the vertex of one of the triangles. Such a triangular grid can be created using the Delauney triangulation method. Irregular polygons created during a segmentation process were used to represent the individual trees of 5 m and higher. The areas for which percent cover is calculated ("Convex Hull") were created based on groups of trees (three each) defined by the vertices of the triangles.
Method 2	Straub et al., 2008 [54]	The second method uses only the polygons representing individual tree crowns from the segmentation
Method 3	Wang et al., 2007, 2007, 2008 [27–29]	The third method uses only the pixels representing forest vegetation with a height of at least 5 m on the Canopy Height Model

Figure 6. The example of the vectorization results.

2.6. Statistical Analysis

The accuracy of the above methods on the selected group of 270 test plots (10×10 m^2) and 30 test plots (30×30 m^2) in the Milicz study area according to the definition formulated by FAO/UN and Kyoto Protocol was evaluated using Mean Bias Error (MBE), Root Mean Square Error (RMSE%) and Mean Absolute Percentage Error (MAE%) according to the following formulas:

$$MBE = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \tag{1}$$

$$RMSE\% = \frac{RMSE}{\overline{y}} * 100 \tag{2}$$

where

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \tag{3}$$

$$MAE\% = \frac{MAE}{\overline{y}} * 100 \tag{4}$$

where

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{5}$$

where

n is the number of observations (270 test plots (10×10 m^2) and 30 test plots (30×30 m^2)),

y_i is the reference area of forest vegetation, $\hat{y}_i$ is the estimated area of forest vegetation by Method 1, 2 or 3.

$\overline{y}$ is the mean of the observed area of forest vegetation.

The estimated area of forest vegetation by Method 1, 2 or 3 and reference data were also compared using a Pearson correlation coefficient (R).

2.7. Limitations of the Study

The study refers to the estimation of the areas of forest vegetation according to the international definitions (height, canopy, area of forest complex). It does not take into account land use and the determination of areas that constitute forests or non-forests, regardless of forest vegetation. The study is based on the level of polygons representing the tree canopy from the segmentation of objects, manual vectorization of the tree canopy model, statistical tests, etc., which have their own accuracy and limitations. Natural forest characteristics may also influence the results. All three methods can be performed using a tree canopy height model and appropriate software, e.g., ArcGIS or QGIS.

2.8. Assumptions and Boundary Conditions

Based on the specificity of the methods tested, Method 2 [54] was assumed to be closest to the analysis results using the reference data. Method 1 [50–53] accounts for the area between the crowns of individual trees that resulted from triangulation, which may result in an overestimation of the area with forest vegetation. Method 3 [27–29], on the other hand, does not consider the area of tree crowns below the required threshold, which may lead to an underestimation of the area with forest vegetation.

To perform the analysis, a model of tree canopy height with a maximum size of 1m pixel generated from a dense point cloud is required. In addition, the detection of individual trees needs to be mapped. Moreover, tools for data processing and spatial analysis (e.g., QGIS or ArcGIS) are required.

3. Results

Of the 270 test plots, 181 were a forest according to the FAO/UN definition and 189 according to the UNFCCC definition. Out of 30 test plots, 23 were a forest as per FAO/UN definition and 23 as per UNFCCC definition. The accuracy of the above methods was verified by manual vectorization performed on a selected set of 270 test plots ($10 \times 10 \text{ m}^2$) and 30 test plots ($30 \times 30 \text{ m}^2$) in the Milicz study area according to the definition formulated by FAO/UN and Kyoto Protocol. The results are presented in Table 5.

Classification accuracy varied between the Methods; independently of scale (10 m or 30 m) and the definition (FAO/UN or Kyoto), the highest levels of accuracies were obtained for classification by Method 2 and the values of overall accuracy and Kappa were very high (OA > 97%, Kappa > 0.94). It is worth noticing that Method 3 resulted in the same excellent accuracies in the case of 30 test plots per UNFCCC definition. Method 1 turned out to be the worst option and resulted in 83% < OA < 93% and 0.38 < κ < 0.79.

The area of forest vegetation accuracies are shown in Table 5. On the basis of these results, we can state that among analysed methods, Method 2 was the most accurate one in the case of both definitions, with the values of RMSE% and MAE% less than 3% independently of the grid size (200 m or 30 m). Strong linear correlations between estimated Method 2 values of the area of forest vegetation and reference data were observed ($R^2 \approx 0.99$, Figures A1–A12). Additionally, Method 2 resulted in the lowest MBE values (Figures A1–A12).

Table 5. The number of test plots (10 × 10 m^2 and 30 × 30 m^2) with the forest vegetation of ≥10% according to particular methods and definitions.

Definition	Method 1	Method 2	Method 3	Reference
		270 test plots FAO/UN		
Forest plots	214	187	167	181
Overall accuracy	87.8%	97.8%	94.8%	*n*/a
Kappa	0.69	0.95	0.89	*n*/a
Commission	18.2%	3.3%	*n*/a	*n*/a
Omission	*n*/a	*n*/a	7.7%	*n*/a
		270 test plots UNFCCC		
Forest plots	232	196	198	194
Overall accuracy	84%	97.4%	96.7%	*n*/a
Kappa	0.55	0.94	0.92	*n*/a
Commission	22.8%	3.7%	4.8%	*n*/a
Omission	*n*/a	*n*/a	*n*/a	*n*/a
		30 test plots FAO/UN		
Forest plots	25	23	21	23
Overall accuracy	93.3%	100%	93.3%	*n*/a
Kappa	0.79	1	0.83	*n*/a
Commission	8.7%	0%	*n*/a	*n*/a
Omission	*n*/a	0%	8.7%	*n*/a
		30 plots UNFCCC		
Forest plots	28	23	23	23
Overall accuracy	83.3%	100%	100%	*n*/a
Kappa	0.38	1	1	*n*/a
Commission	21.7%	0%	0%	*n*/a
Omission	*n*/a	0%	0%	*n*/a

Inconclusive results were achieved for Method 3. Method 3 resulted in moderate accuracies, with an RMSE% and MAE% less than 20% according to UNFCCC protocol and strong linear correlation (($R^2 > 0.96$, Figures A1–A12). Method 3 worked the worst in the case of the second definition ($51\% \leq RMSE\% \leq 56\%$, MAE% ≈ 27%, $0.60 \leq R^2 \leq 0.64$). The values of the measurements underestimate the forest area in case of the FAO definition and they overestimate the forest area due to the Kyoto definition.

Conversely, Method 1 provided the largest errors (RMSE% from 68.7% to 97.8% and MAE% from 57.8% to 70.3%). The values of Pearson correlation coefficient for that method varied from 73.5% to 83.7%. High positive values of the MBE means that measurements by Method 1 overestimate the area of forest vegetation (Table 6, Figures A1–A12).

Table 6. Results comparison for the methods according to the FAO/UN and the Kyoto Protocol definitions.

Definition	Method 1	Method 2	Method 3
270 test plots FAO/UN			
MBE	123.87	−0.76	−33.90
RMSE%	97.8%	3.0%	55.8%
MAE%	70.3%	2.1%	27.3%
R^2	0.50	0.998	0.64
270 test plots UNFCCC			
MBE	115.31	−1.10	20.34
RMSE%	79.3%	3.0%	18.4%
MAE%	57.8%	2.1%	10.4%
R^2	0.54	0.99	0.96
30 test plots FAO/UN			
MBE	1114.83	−6.80	−305.07
RMSE%	86.2%	1.1%	51.4%
MAE%	70.3%	0.9%	26.6%
R^2	0.65	0.99	0.60
30 test plots UNFCCC			
MBE	1037.83	−9.87	183.03
RMSE%	68.7%	1.7%	15.4%
MAE%	57.8%	1.3%	10.2%
R^2	0.70	0.99	0.97

4. Discussion

The study refers to the estimation of areas of forest vegetation according to the international definitions (height, canopy cover, area of forest complex). It does not take into account land use and the determination of area representing forests or non-forests regardless of forest vegetation. The study is based on the layer of polygons representing tree canopy from object segmentation, Canopy Height Model manual vectorization, statistical tests, etc., which have their own accuracy and limitations. Natural forest characteristics may also influence the results. All three methods may be performed using a Canopy Height Model and the suitable software, e.g., ArcGIS or QGIS.

Classification accuracy varied between the methods independently of scale and the definition, the highest levels of accuracies were obtained for classification by Method 2, values of overall accuracy and Kappa were very high (OA > 97%, Kappa > 0.94). Method 3 resulted in the same excellent accuracies in the case of 30 test plots per UNFCCC definition. Method 1 turned out to be the worst option.

There are many approaches to forest area delineation based on remote sensing data. In this paper, we focus on the use of airborne laser scanning data and the estimation of three variables that determine the presence of forest vegetation in the international forest definitions: elevation, crown projection area, and forest complex area, which have not been fully addressed in previous work. In the work, we use three methods for calculating tree canopy cover proposed by: Eysn et al. and Sackov and Kardos [50–53] (Method 1); Straub et al. [54] (Method 2) and Wang et al. [27–29] (Method 3). However, no publication was found comparing the methods used to calculate the degree of canopy cover with each other and with the reference data. Method 2 was the most accurate for both definitions, with values of RMSE% and MAE % of less than 3% regardless of grid size (200 m or 30 m) and a

strong linear correlation between the results and the reference data of R2 ≈ 0.99. Method 3 resulted in moderate accuracies, with an RMSE% and MAE% of less than 20% according to the UNFCCC protocol and the linear correlation of $R^2 > 0.96$. Method 1 performed worst in the case of the UNFCCC definition. The accuracy obtained in our study (83.3–100%) is comparable to the accuracy of Haapanen [20]—80–91%, Straub [54]—97.7%, Sackov and Kardos [53]—93%, Pekkarinen [30]—80–90%, Eysn [50–52]—96–98.4%, Pujar [36]—76–79%, Kolecka [34]—95% and Naesset [26]—random errors of 1–4.6%.

In the case of the FAO/UN definition, Methods 1 and 2 overestimate forest area and Method 3 underestimates it. In the case of the Kyoto Protocol definition, all definitions overestimate the forest area compared to the reference data. This is true for the accuracy analysis of 270 sample plots (100 m² area). For the analysis of 30 sample plots (900 m² area), Method 1 overestimates the forest area, and Methods 2 and 3 reach the accuracy limit of 100%.

It is worth noting that the minimum area of forest land according to FAO/UN and UNFCCC definitions is 0.1 ha, which is slightly more than the largest sample plots in terms of the area used in our study. It is reasonable to assume that the smaller the scale of the analysis (i.e., the larger the area analyzed), the smaller the differences between the results, which is particularly important when reporting a country-wide forest area.

Aerial and satellite imagery, as well as data from airborne laser scanning [38–47], allows for segmentation and thus the creation of polygons representing the crowns of individual trees with a given projected area. It is possible to use multiple aerial images and to obtain the height information using the stereo matching method [59], which creates a three-dimensional data space from the two-dimensional images. Unfortunately, this method is susceptible to illumination conditions and provides less accurate results when there are many shadows on the input images. Airborne laser scanner data is resistant to this problem.

For accuracy analysis, a reference in the form of manual vectoring of the areas with forest vegetation on the sample plots, canopy height model and orthophotomap was used and was supported by the individual tree height and canopy data (measured in 4 directions) from the sample plots. Such distance data used to collect reference information can be considered to be a very good and accurate data source. In addition, the reference data were also performed manually by Eysn [50–52], Sackov and Kardos [53], Wang [27–29], Straub [54]. Kolecka [34] and Pekkarinen [30], who performed the accuracy analysis based on the test points or polygons. Pujar [36] performed only the visual analysis. Finally, we assume that the reference data we used is accurate enough. We can assume that the best option for reference data would be to measure all trees on the sample plots, including height and crown size, measured in 8 directions. This would of course require an incomparably larger amount of work. Nevertheless, we are confident that the reference data used in this study are reliable and often better than those used in other studies of this type.

The high cost of analyses over increasingly large areas should also be noted. Since the difference between the results obtained becomes smaller as the area size increases, the method with the lowest processing costs and times should be chosen. The least demanding method in this respect is Method 3 and should be considered as an alternative when analyzing large areas, as it has a similar accuracy to Method 2.

In this paper, for the first time, methods for determining the area for which canopy cover is calculated (using data from (ALS) are compared and the differences between them in terms of accuracy (the agreement between the results and the reference data) and the complexity of the process (time and effort required to perform the analysis) are discussed. The area with forest vegetation is a starting point for the assessment of forest area according to the international definitions, taking into account land use and its future evolution, even without the current forest vegetation. This in turn is important in the context of reporting, estimating carbon stocks and biodiversity to mitigate the effects of climate change.

International organizations such as the FAO/UN and the UNFCCC require signatory countries to maintain and increase the area of forests and other areas with forest vegetation.

The methodology proposed in this article can help monitor afforestation with a similar and objective methodology. Forests play an important role in the accumulation of carbon stocks, the release of which into the atmosphere would increase the negative effects of climate change. In addition, forests are important for biodiversity, provide environmental services and influence quality of life and health [60,61]. Therefore, by using good forest monitoring methods, we are not only improving this tool, but also solving many other problems that contribute to the management and protection of forests. Above all, however, we are helping to create a forestry policy based on a consistent, objective and uniform methodology.

5. Conclusions

This paper is the first to compare three consistent, objective, and uniform methods for defining the area for which canopy cover is calculated (using ALS data) to define forest area. Two forest definitions were used: UNFCCC and Kyoto, and analyses were conducted at different spatial scales. Differences between the methods used were discussed in terms of accuracy (agreement of results with reference data) and complexity of the process (time and effort required to perform the analysis).

Of the methods tested, Method 2 proved to be the most accurate for both definitions (UNFCCC and Kyoto). Strong linear correlations were found between the values of the forest vegetation area estimated by Method 2 and the reference data. Method 1 was found to be the worst option. Method 1 contained the largest errors and overestimated the forest vegetation area.

The complexity of the methods was related to the need to invest more time and equipment in their implementation. Since the difference between the results of the different methods becomes smaller as the size of the analyzed area increases, the method with the least effort for its implementation should be chosen. The least demanding method in this respect is Method 3, which should be considered as an alternative for large-scale analyses due to its similar accuracy to Method 2.

The results obtained are important for the management and protection of forest areas. Accurate and efficient estimation of forest area is important for reporting, carbon stock estimation, forest conservation and management, afforestation monitoring and biodiversity monitoring for climate change mitigation.

Author Contributions: T.H. performed the literature search, conceptual planning, analysis, writing the text and editing. A.K. helped with the statistical analyses, reviewed the text and edited it. K.S. carried out the conceptual plan, provided data and funding for the study, reviewed and edited the text. All authors have read and agreed to the published version of the manuscript.

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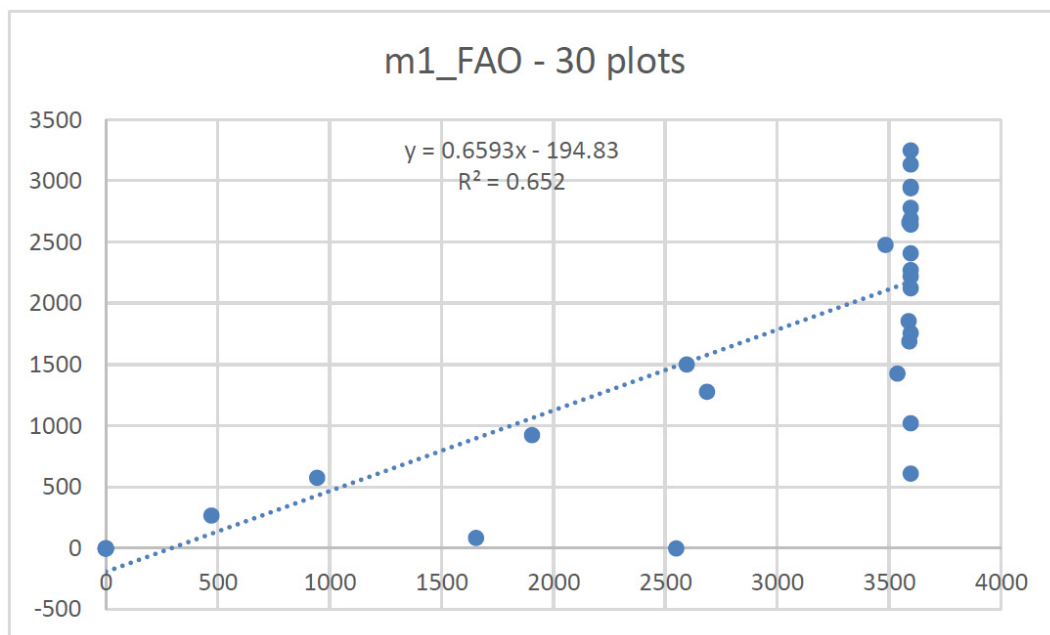**Conflicts of Interest:** The authors declare no conflict of interest.

Appendix A

Figure A1. The reference area compared to the estimated forest area according to Method 1 for test plots (30 × 30 m^2) as defined by FAO/UN.
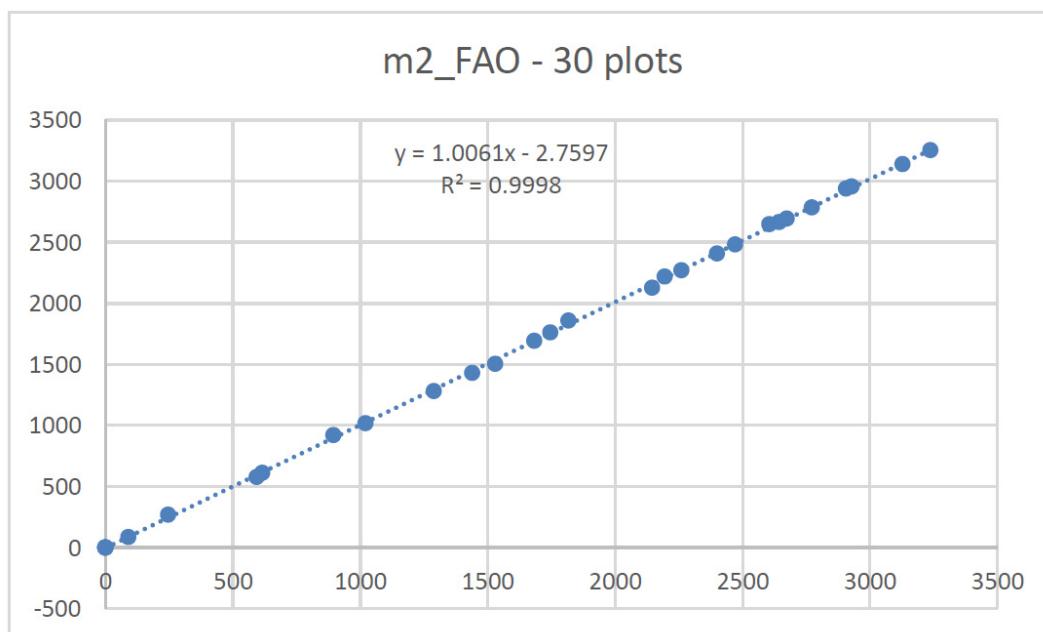

Figure A2. The reference area compared to the estimated forest area according to Method 2 for test plots (30 × 30 m^2) as defined by FAO/UN.
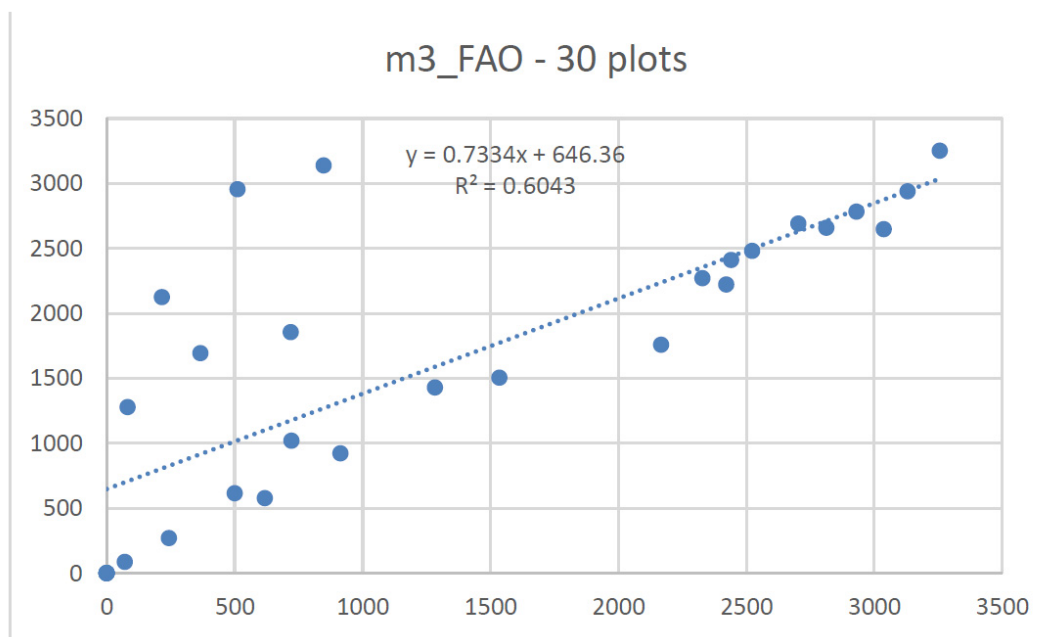
Figure A3. Reference area compared to estimated forest area by Method 3 for test plots (30×30 m^2) according to FAO/UN definition.
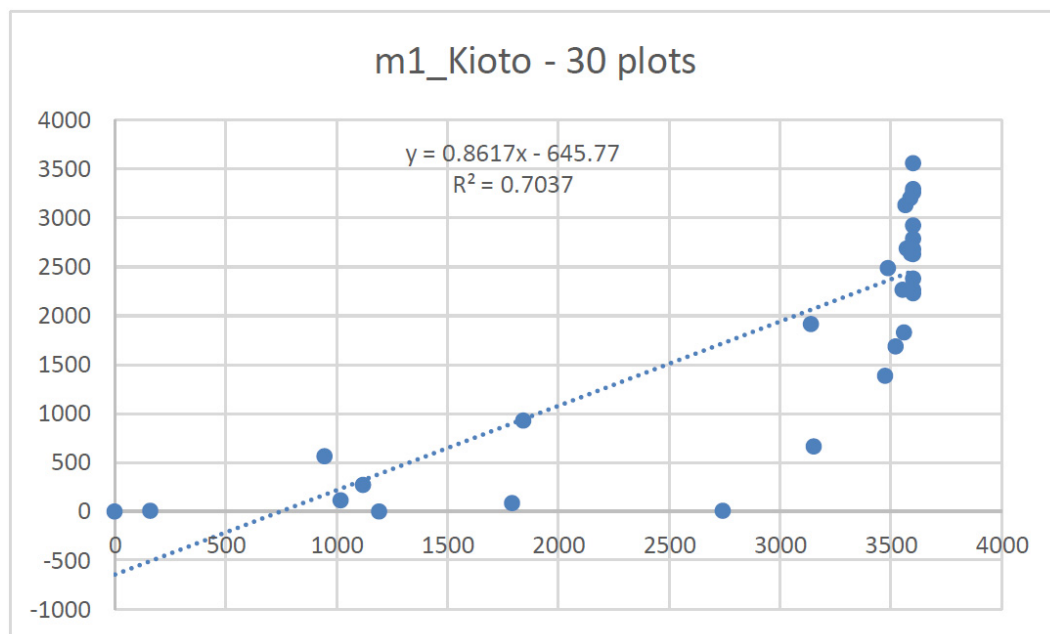

Figure A4. Reference area compared to estimated forest area by Method 1 for test plots (30×30 m^2) as defined by the UNFCCC.
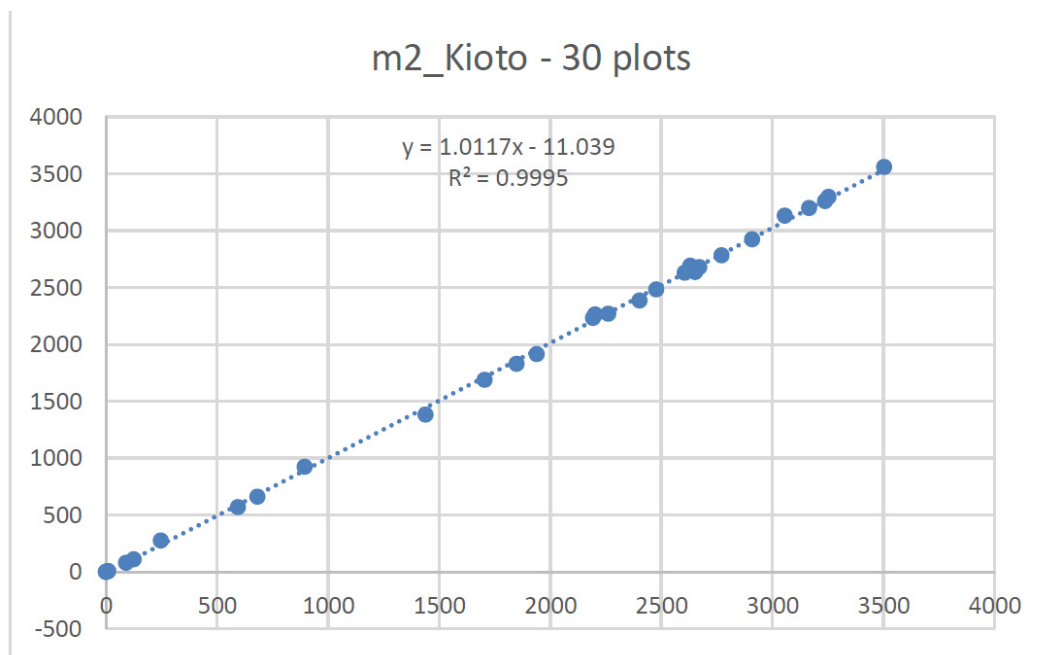
Figure A5. The reference area compared to the estimated forest area using Method 2 for test plots (30 × 30 m^2) as defined by the UNFCCC.

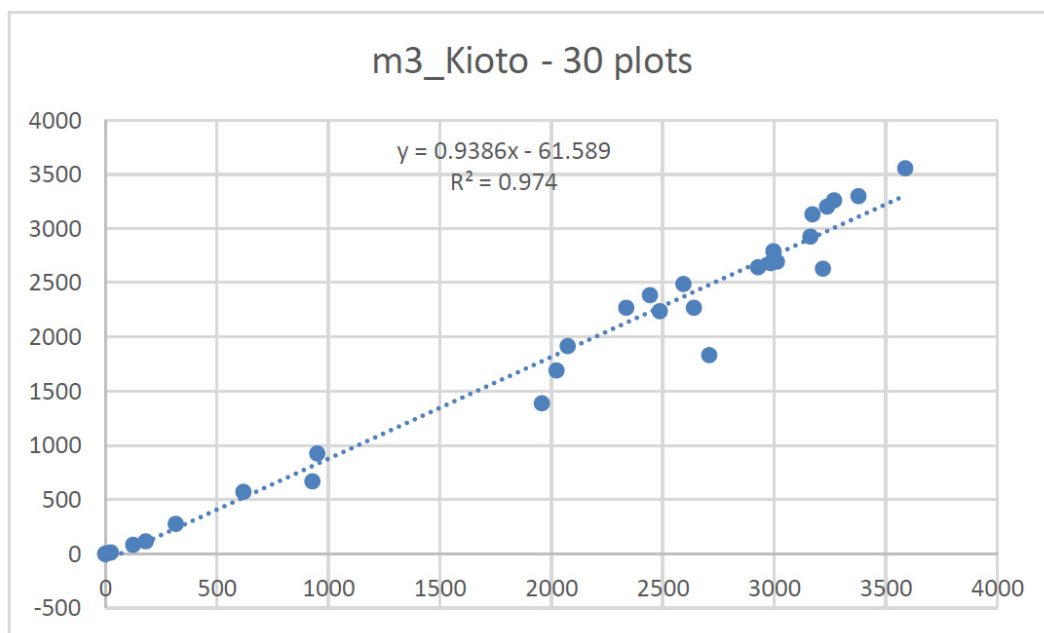**Figure A6.** The reference area compared to the estimated forest area by Method 3 for test plots (30 × 30 m^2) according to the UNFCCC definition.
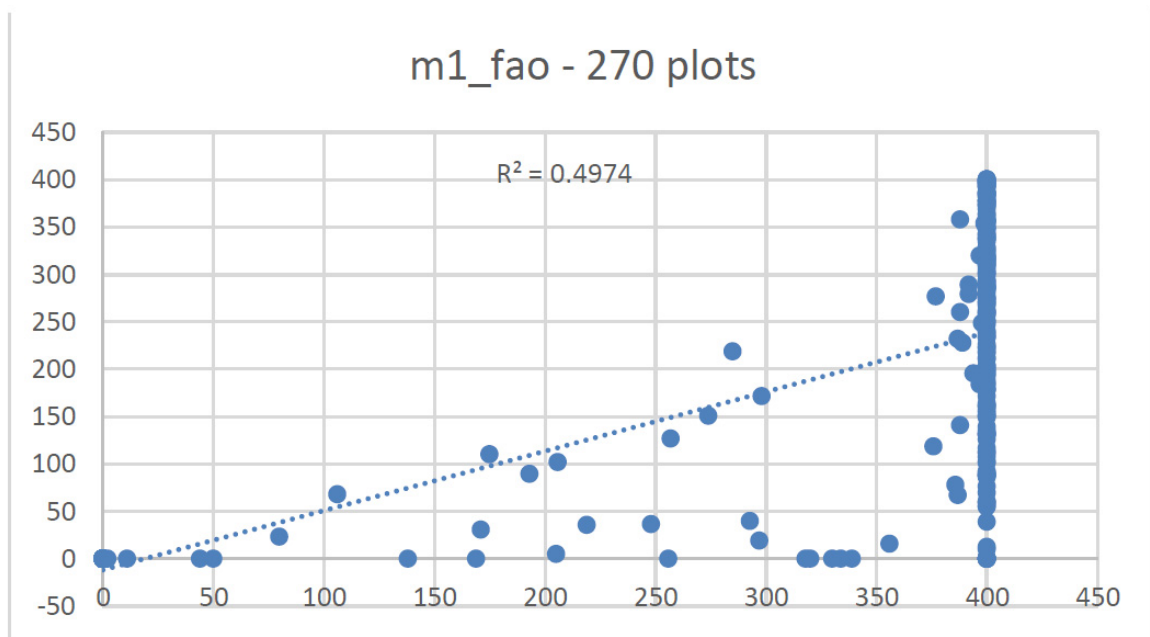
Figure A7. Reference area compared to estimated forest area by Method 1 for test plots (10×10 m^2) according to FAO/UN definition.
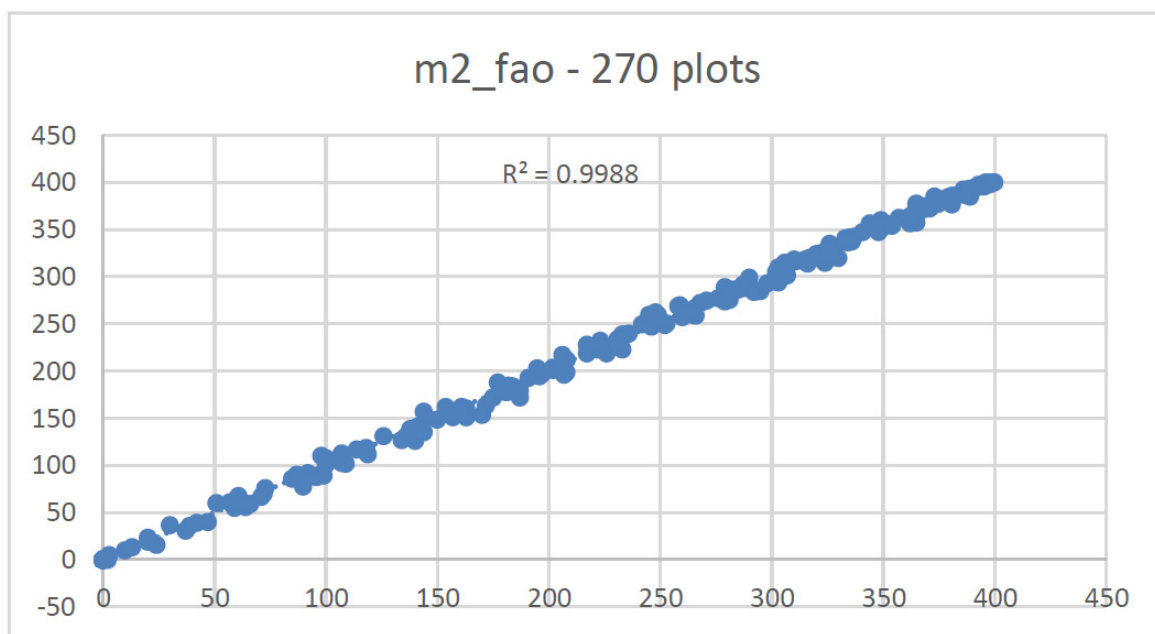

Figure A8. The reference area compared to the estimated forest area according to Method 2 for test plots (10×10 m^2) as defined by FAO/UN.
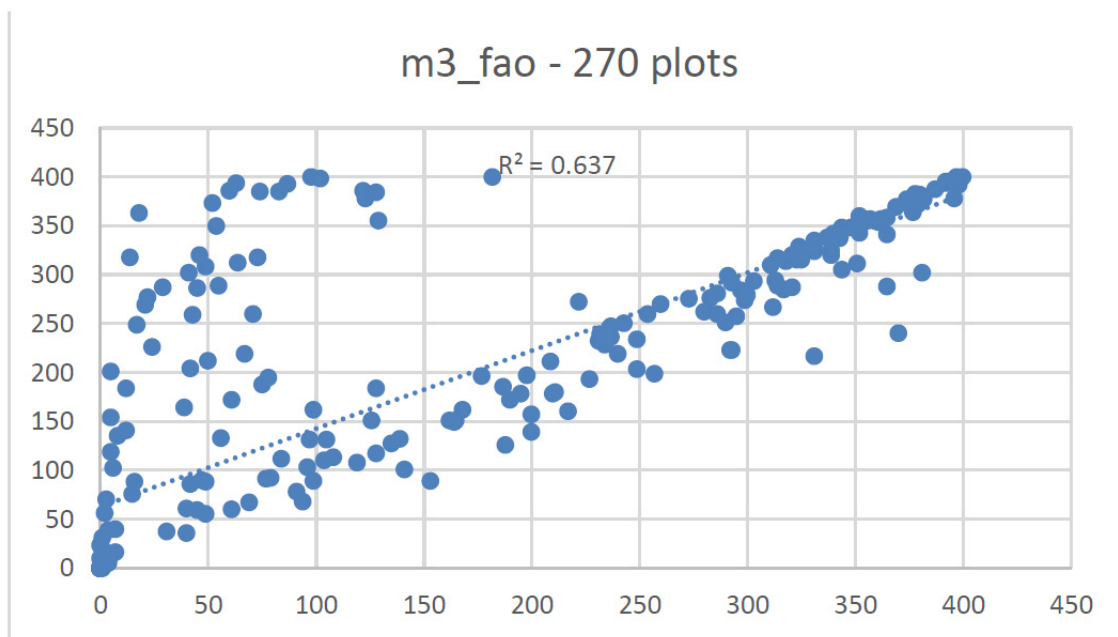
Figure A9. Reference area compared to estimated forest area by Method 3 for test plots (10×10 m^2) according to FAO/UN definition.
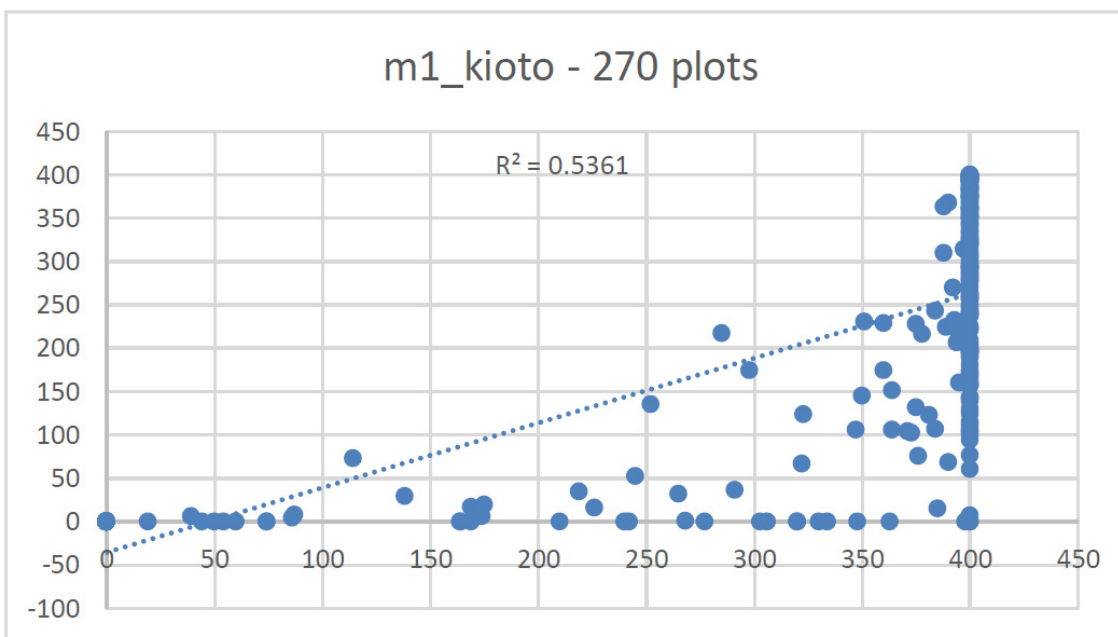

Figure A10. Reference area compared to estimated forest area by Method 1 for test plots (10×10 m^2) as defined by the UNFCCC.
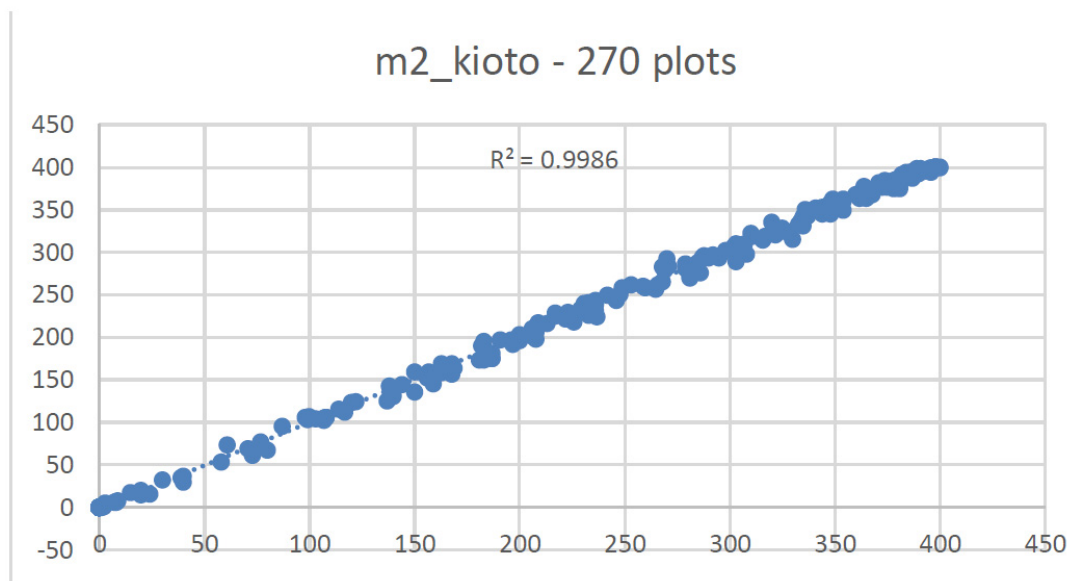
Figure A11. Reference area compared to estimated forest area by Method 1 for test plots (10 × 10 m²) as defined by the UNFCCC.

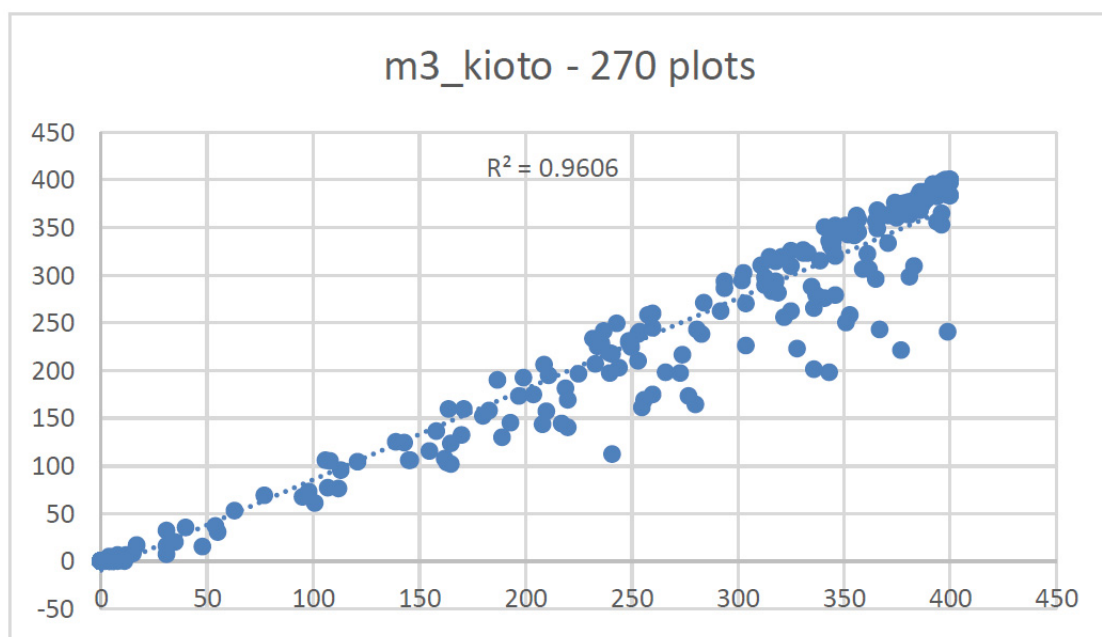**Figure A12.** Reference area compared to estimated forest area by Method 1 for test plots (10 × 10 m²) as defined by the UNFCCC.

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