

# Construction Method of Voxel Model and the Application for Agro-Forestry

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**Abstract:** Agroforestry is cultivating agricultural crops and useful plants in a forest. Thus, it is important to analyze and construct the environment suitable for the cultivation of useful plants for agroforestry. Moreover, the precise determination of the forest biomass and solar radiation in a forest floor by remote sensing is very important for ecological and economic considerations in agroforestry. In order to estimate biomass, 3D information of complex structures of the forest should be captured. Furthermore, solar radiation in the forest floor, at various land cover should be estimated. A shielding situation of direct solar radiation has especially affected a growth of plants in a forest floor. An aerial and ground-based LiDAR (Light Detection And Ranging), and digital photos are often used for modeling the three dimensional structure of forest environment. Point clouds data were obtained by LiDAR measurement, and SfM (Structure from Motion) technique from the digital photos. An approach to 3-D tree modeling based on point cloud data was converted to voxel. Voxel model is the 3D raster domain, which is a discrete 3D space with elements called voxels (G. Ben, P. Norbert 2004). Using voxel model, the density of point cloud can become homogeneous and the quantity of data can become reduced. In this paper, the construction method of voxel model of the forest was explained and 2 applications of voxel model for forest environment analysis such as estimating forest biomass and solar radiation were introduced. The result showed LAI (leaf area index) was 0.0074ha and woody material volume was 7.25m<sup>3</sup> on 0.009ha of test area. Estimated value and measured value of solar radiation showed same trend.

**Keywords:** Point cloud, Voxel model, Leaf area, Woody material volume, Solar radiation

## 1. Introduction

Agroforestry is cultivating agricultural crops and useful plants in a forest. Thus, it is important to analyze and construct the environment suitable for the cultivation of useful plants for agroforestry. An aerial and ground-based LiDAR (Light Detection And Ranging), and digital photos are often used for modeling the 3-D structure of forest environment. We

can get the point clouds data by LiDAR measurement, and SfM (Structure from Motion) technique using the digital photos. An approach to 3D tree modeling based on point cloud data can be converted to voxel representation. The voxel model is the 3D raster domain, which is a discrete 3D space with elements (Ben and Norbert, 2004). Previous studies tried to retrieve forest inventory variables using voxel model

of LiDAR point cloud data (Hosoi and Omasa, 2013; Bienaert et al., 2010). Hosoi and Omasa (2013) proposed a method for accurate woody material volume estimation based on a 3-D voxel-based solid modeling of the tree from LiDAR data. The solid model was composed consecutive voxels that filled the outer surface and the interior of stem and large branches. By using the model, the woody volume can be computed by counting the number of corresponding voxels to woody materials and multiplying the result by the pre-voxel volumes of them (Hosoi and Omasa, 2013). Therefore, various attribute values to each voxel cell (Figure 1.1) for estimating forest inventory variables can be stored. In addition, voxel representation has an advantage of homogenization of the point cloud density and reducing the data size.

Firstly, construction method of the voxel model of the forest around Kanamine Shrine located in Nakagonyu district in Kami City, Kochi Prefecture was explained.

Secondly, the method of estimating LAI (leaf area index) and forest biomass by assign attribute values was introduced.

Finally, the method of estimating solar radiation by using the leaf shielding ratio was also introduced.

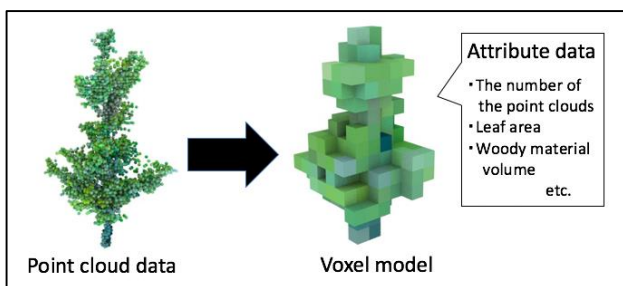


Figure 1.1 Overview of voxel model

## 2. Construction method of the voxel model of the forest

Figure 2.1 shows the flow chart of voxel model. The procedures of the construction method of the voxel model are the three steps; Point cloud acquisition, registration and voxelization.

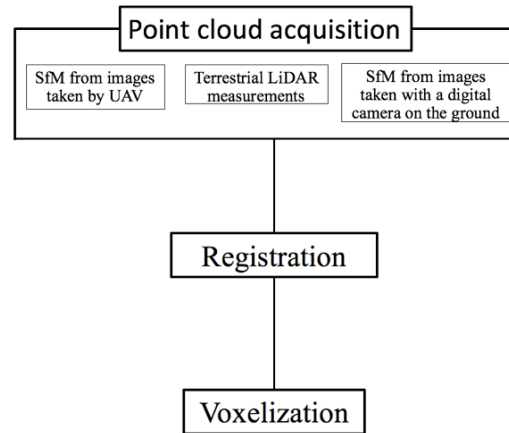


Figure 2.1 Flow chart of voxel model construction

### 2.1 Study area

The study area is around Kanamine Shrine located in Nakagonyu district in Kami City, Kochi Prefecture (Figure 2.2). Figure 2.4 shows the observation extent by a rotary wing unmanned aerial vehicle (UAV), and Figure 2.5 shows the extent for constructing the voxel model. Trees such as Japanese cedar and Shi · oak were grown around Kanamine Shrine (Figure 2.3).

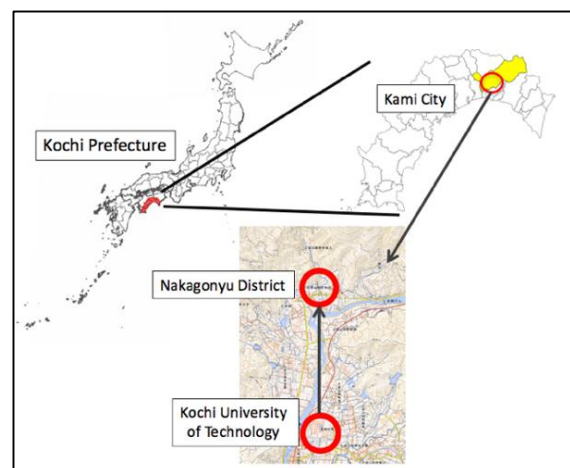


Figure 2.2 Location for study area



Figure 2.3 Kanamine Shrine

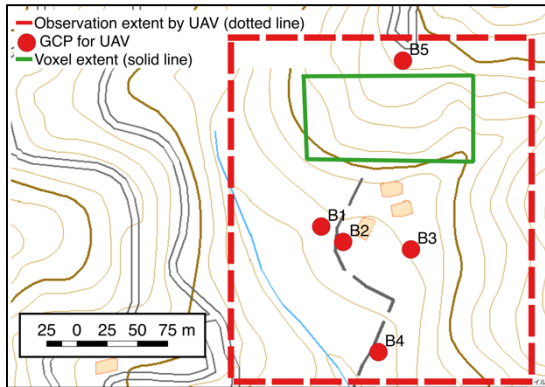


Figure 2.4 The observation by the UAV

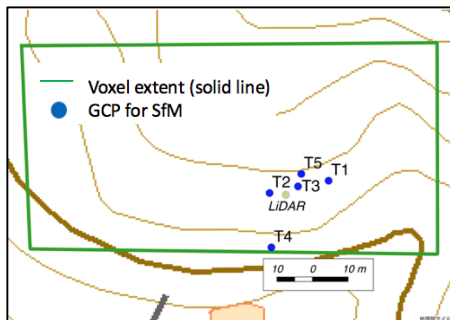


Figure 2.5 The extent for voxel model

## 2.2 3D data acquisition

Point cloud data obtained by SfM from both images taken from the sky with UAV and images taken with a digital camera on the ground. The point cloud data obtained from measurement by terrestrial LiDAR were merged to create a voxel model.

### 2.2.1 SfM from images taken by UAV

SfM is a method of simultaneously restoring the position of the camera of the scene and the point cloud

data from a plurality of images captured while changing the viewpoint of the camera.

In this study, the Boomerang, which is a rotary blade type UAV manufactured by GWING Co., Ltd. and equipped with a digital camera SONY  $\alpha$  7 mounted a lens with a focal length of 28 mm, was used to take the aerial photos. The UAV flight route, ground altitude, speed, and shooting interval were set up. The overlapping ratio of the photos were 90% or more and the side lap was 75% or more. Totally 165 images were taken. The ground control marker for UAV shown in Figure 2.6 was set at the reference ground control points B1 to B5 in Figure 2.4 in order to be used for the geometric transformation of point cloud data derived by SfM. The photographed image was processed by PhotoScan which is SfM software manufactured by Agisoft Corporation and point cloud of the surface was prepared. The obtained point clouds have the relative coordinates and RGB values as attribute data. Figure 2.7 shows the point cloud image obtained by SfM technique using the digital photos taken by UAV.

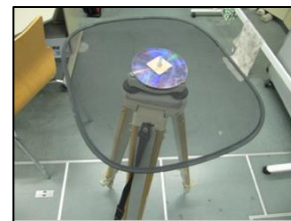


Figure 2.6 Ground control marker for UAV



Figure 2.7 The point cloud obtained by SfM from UAV

### 2.2.2 Terrestrial LiDAR measurements

LiDAR is a remote sensing technology that can acquire information such as the distance, angle, reflection intensity, etc. by irradiating laser to the object to be measured and measuring its reflected light. The GLS-1500 manufactured by TOPCON Co. was used in this study (Table 2.1). The terrestrial LiDAR was set up at the position shown in Figure 2.5, and the measurement range was set to 360° in the horizontal direction and to ± 35° in the vertical direction. In addition, the measurement intervals for both the azimuth angle and the altitude angle were set to 0.05°, respectively. Figure 2.8 shows the acquired point cloud by terrestrial LiDAR.

Table 2.1 Specifications of LiDAR

Products of Laser Scanner	GLS-1500
Effective measurement range	500m
Measurement angle	70 × 360
Ranging accuracy	±4mm (in 150m)
Measurement density	Max 1mm (in 20m)
Max points	100,000,000 points
Measurement principle	Time of Flight
Wavelength of the laser	1535nm



Figure 2.8 The point cloud obtained by LiDAR

### 2.2.3 SfM from images taken with a digital camera on the ground

By obtaining point cloud by SfM from the image taken on the ground with the digital camera PENTAX

k-30 on the ground, the portion where the LiDAR cannot be measured were supplemented. At that time, photographing was performed the overlap of the photograph was 60% or more. Totally about 300 images were taken. Figure 2.9 shows the obtained point cloud by SfM from the images taken with a digital camera on the ground.



Figure 2.9 The obtained point cloud by SfM

### 2.3 Registration

Since each point cloud acquired by SfM and LiDAR has individual coordinate system, registration of point cloud data must be carried out to convert common coordinate system by 3D affine transformation using ground control points, which are shown in Figure 2.4 and 2.5. Thus, these point clouds were registered into common coordinate system, which is corresponding to voxel coordinate. Table 2.2 shows registration accuracy.

Table 2.2 registration accuracy

RMSE	X(m)	Y(m)	Z(m)
SfM from images taken by UAV	0.002	0.009	0.006
Terrestrial LiDAR measurement	0.017	0.001	0.001
SfM from images taken with a digital camera on the ground	0.002	0.001	0.003

## 2.4 Voxelization

The size of voxels in this study was 20 cm and all points within the registered data converted into voxel coordinates. Figure 2.10 shows the procedures of voxelization. The coordinates of the center position of the voxel, the average value of the RGB of the point clouds in the voxel, and the number of the point clouds in the voxel were stored to each voxel cell as attribute values. Figure 2.11 shows the constructed voxel model around Kanamine Shrine.

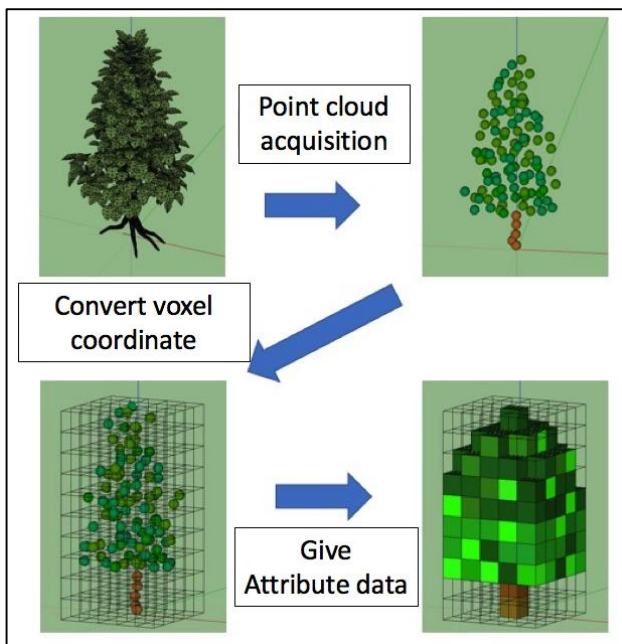


Figure 2.10 Procedures of Voxelization

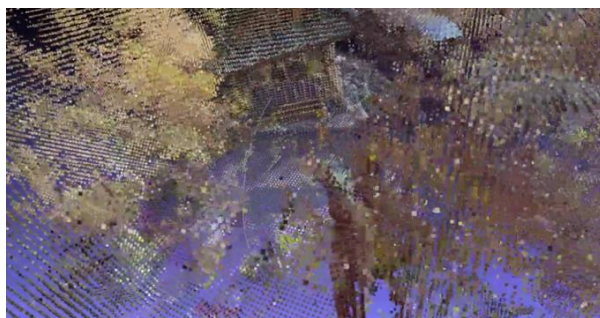


Figure 2.11 The voxel model of around Kanamine Shrine

## 3 Estimation of LAI and woody material volume

### 3.1 Method of the estimation

Various attribute values to each voxel cell can be assigned to estimate various forest inventories. Firstly, method to assign leaf area and woody material volume to each voxel cell as attribute values was explained. The point cloud was classified into leaf or woody material by RGB data.

The relationship between the real leaf area and the number of point classified into leaf, and the relationship between the real woody material volume and the number of point classified into woody material are examined respectively. The coefficients of linear conversion to estimate leaf area and woody material and they were assigned to each voxel cell as attribute values. Measurements object was evergreen broad-leaved tree *Quercus glauca* shown Figure 3.1.



Figure 3.1 Measurement object

#### 3.1.1 Classification of point cloud

Firstly, point cloud of the tree was acquired using LiDAR from three directions and its voxel model was constructed. Secondly, selected 15 typical points of a leaf and a woody material were used as the training data for the classification. Then the point cloud was classified into leaf or woody material by Euclidean distance between training data and each point. Figure 3.2 shows the classification result. Green represents leaves and red represents woody material.

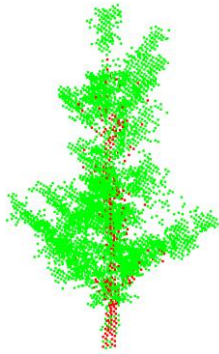


Figure 3.2 Classification result

### 3.1.2 Leaf area measurement

In order to measure the leaf area, all the leaves of *Quercus glauca* are collected. Next, photographs were taken by placing leaves on section paper. Finally, the total leaf area of *Quercus glauca* was counted by the number of pixels per 1 cm<sup>2</sup> printed on the section paper on the image.

As a result of the measurement, since the number of pixels of the leaves was 72,770,183 pixels and the number of pixels per 1 cm was 19,322.8 pixels, the leaf area of the whole *Quercus glauca* was 3776.04 cm<sup>2</sup>.

### 3.1.3 Stem volume measurement

A one-liter graduated cylinder was used for the estimation of the stem volume. First branch and stem of *Quercus glauca* were cut with about 15 cm in size. Then 800 ml water put in a measuring cylinder exactly. Finally the stem was sunk with the volume.

As a result of the measurement, the volume of the stem was 119 ml.

### 3.1.4 Assign value

Table 3.1 shows total number of point cloud in leaf and the corresponding actual total leaf area. Table 3.2 shows total number of point cloud in wood and the corresponding actual total woody material volume. The spatial density of point cloud can be calculated from distance between target tree and LiDAR position.

Assign value in each voxel was derived using those measurement result and the spatial density of point cloud. Table 3.3 shows assign value oh leaf area and woody material volume.

Table 3.1 Result of measurement for leaf area

Number of point of leaf	Leaf area
3,731	3776.04(cm <sup>2</sup> )

Table 3.2 Result of measurement for woody material volume

Number of point of wood	Woody material volume
389	119.0(cm <sup>3</sup> )

Table 3.3 Assign value

The number of point clouds in voxel	Conversion coefficients	
	Leaf area	Woody material volume
Only 1	0.25(cm <sup>2</sup> )	0.125(cm <sup>3</sup> )
2 or more	1.29(cm <sup>2</sup> )	0.396(cm <sup>3</sup> )

## 3.2 Application of the conversion coefficients

Using the conversion coefficients, woody material volume and LAI are obtained from voxel model. The test area is *Cinnamomum camphora* forest in the Kagamino Park near Kochi University of Technology.

### 3.2.1 Voxelization

Point cloud data of the *Cinnamomum camphora* forest was acquired on September 26, 2014. Figure 3.3 shows the observation site by UAV and LiDAR, and the range for the voxel model. The voxel extent is 30m × 30m. The obtained point cloud was classified as leaf or stem.

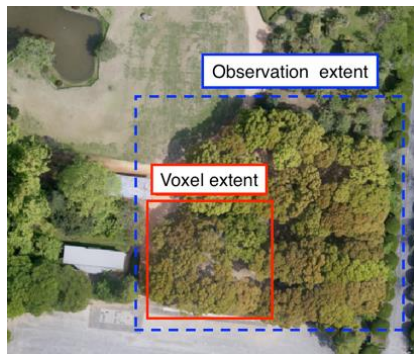


Figure 3.3 Observation range

The size of voxels in this study was 10 cm. As the attribute, the average coordinates of the point clouds, the average RGB value, the number of the leaf point clouds, the number of the trunk point clouds were stored. The point cloud of leaves and stems in the voxel were converted to leaf area and woody material volume by using the conversion factor.

### 3.2.2 Estimation result

LAI means the total leaf area per 1 m<sup>2</sup>. The total leaf area per unit area can be computed by summing the leaf area in the voxels. In addition, the woody material volume of the voxel model can be calculated by summing the total woody material volume of the all voxels. Figure 3.4 shows the distribution of LAI calculated from the voxel model and Figure 3.5 shows the distribution of woody material volume per unit area. Using voxel model, the distribution of forest resources can be visualised.

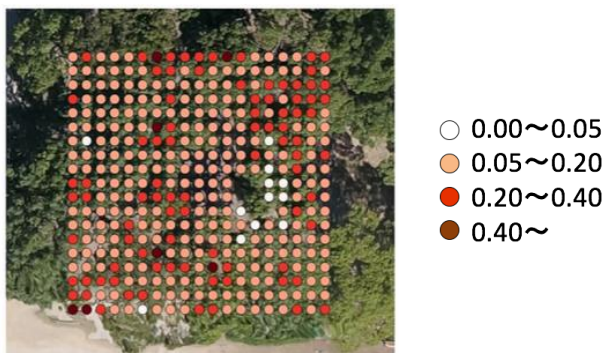


Figure 3.4 Estimation result of LAI

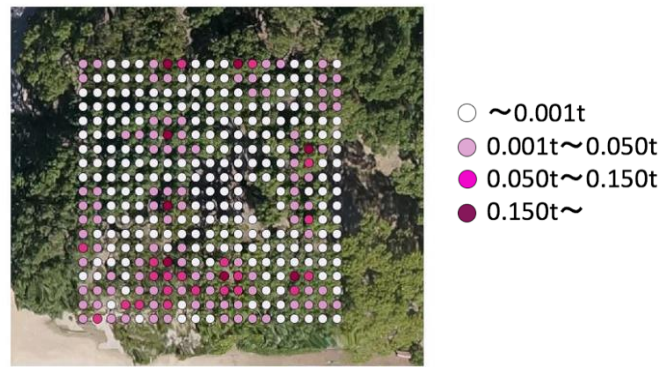


Figure 3.5 Estimation result of woody material volume

## 4 Estimation of solar radiation

Hemispherical photograph is often used when estimating the solar radiation in a forest floor. The solar radiation can be estimated using a virtual hemispherical photograph which can be created from the voxel model. The process of the solar radiation estimation method using the virtual hemispherical photograph has 4 steps.

1. Free software called SMARTS\_295 can compute solar radiation or PAR etc. by inputting date and plural atmospheric parameters, instantaneous values of direct solar radiation and scattered solar radiation.
2. A virtual hemispherical photograph with any viewpoint using the voxel model.
3. In the case of no shielding condition, solar radiation at any point at any date can be estimated using hemispherical photograph (Eq.1). The solar radiation estimation can be calculated following equation. (Toda · Nakamura, 2009)

$$W = \sum_{i=1}^{a_1} \frac{P_d}{a_1} + \sum_{j=1}^{a_2-a_1} \frac{P_s}{a_2-a_1} \quad \text{Eq.1}$$

$P_d$ : direct solar radiation (W/m<sup>2</sup>)

$P_s$ : scattered solar radiation (W/m<sup>2</sup>)

$a_1$  : Number of pixels of the sun in the virtual hemispherical photograph

$a_2$  : Total number of pixels of virtual hemispherical photograph

$W$ : solar radiation (W/m<sup>2</sup>)

4. In the case of an obstacle around at any point, the shielding ratio of sunlight is assigned to each pixel of the virtual hemispherical photograph as an attribute value. By using the virtual hemispherical photograph, the solar radiation at any date and time at any point estimated by the following equation.

$$W = \left(1 - \frac{\sum_{i=1}^{a_1} r_i}{a_1}\right) P_d + \sum_{j=1}^{a_2 - a_1} (1 - r_j) \frac{P_s}{a_2 - a_1} \quad \text{Eq.2}$$

$P_d$ : direct solar radiation (W/m<sup>2</sup>)

$P_s$ : scattered solar radiation (W/m<sup>2</sup>)

$a_1$  : Number of pixels of the sun in the virtual hemispherical photograph

$a_2$  : Total number of pixels of virtual hemispherical photograph

$r_i$ : Elimination rate of each pixel

$W$ : solar radiation(W/m<sup>2</sup>)

#### 4.1 Study area

Morella rubra (evergreen broad-leaved tree) located on the site of Kochi University of Technology was target tree (Figure 4.1). The crown diameter is about 9 m and the tree height is about 7 m.

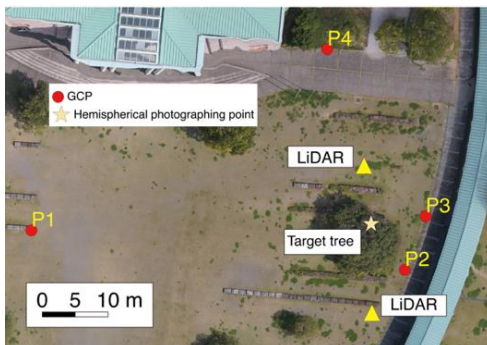


Figure 4.1 Test area

#### 4.2 Survey of the luminance of the sun for calculation the shielding ratio of leaf voxels

The photographs of the sun and the overlapped leaves (Figure 4.2) were taken between 8:30 and 12:00 on December 28, 2016 to January 3, 2017, and the illuminance at that time was measured at the same time. The photographs were taken on the condition that fixed ISO speed at 1600 and auto shutter speed. When the illuminance was measured by flux meter, a cylinder was attached to the sensor so that only direct light was measured as much as possible. Photographing and illuminance measurement were performed at intervals of about 3 minutes. When calculating the luminance value of the sunlight, it is necessary to have the same shooting condition. Therefore, using the property that the luminance value and the shutter speed are inversely proportional each other. Luminance value was calculated under the condition when the shutter speed is 1/1000 this time. For example, in the case of the shutter speed at 1/2000, the brightness value was multiplied by 2. The correlation coefficient between the brightness value of the sun photo and the value of the illuminance showed very high, the correlation coefficient showed 0.93 (Figure 3.4). From this result, shielding ratio of each leaf voxel cell was determined by using the luminance value of the sunlight.

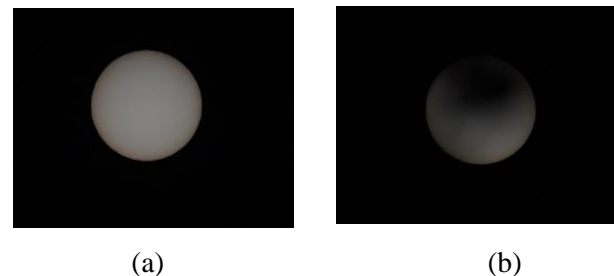


Figure 4.2 Change in luminance value when the sun is hidden by leaves



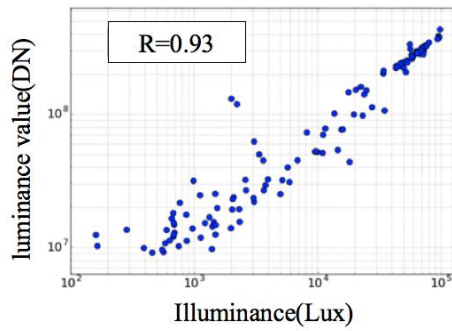


Figure 4.3 Relationship between luminance value and illuminance of sunlight

### 4.3 Voxelization

Firstly, point cloud of target tree was acquired using LIDAR. LIDAR was installed at a distance of about 10 m from the tree and measured from north and south. Secondly, the point clouds were classified into as leaves or woody materials. In the classification, reflection intensity was used rather than color. Finally, the size of the voxel was set to 2 cm because the width of the leaves of the target trees was also 2 cm. Central coordinates of voxel, leaf or trunk attribute were stored as attribution.

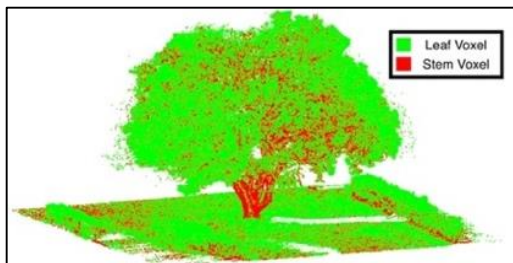


Figure 4.4 Voxel model

### 4.4 Creating virtual hemispherical photograph

Hemispherical photograph is an image obtained by projecting the whole area of the sky on a circular image with a circumference fisheye lens mounted on a digital camera. Any viewpoint on the voxel model cloud be selected and created the same projection image (hereinafter referred to as virtual hemispherical photograph) by Python program. Color in the virtual hemispherical photograph expresses the leaves in

green and the woody materials in red, and the brightness expresses the number of voxels (Figure 4.5(a)). The real photograph taken is shown in Figure 4.5(b). Comparing both images, the virtual hemispherical photograph can express not only the thick stem but also the shape of a thin branch.

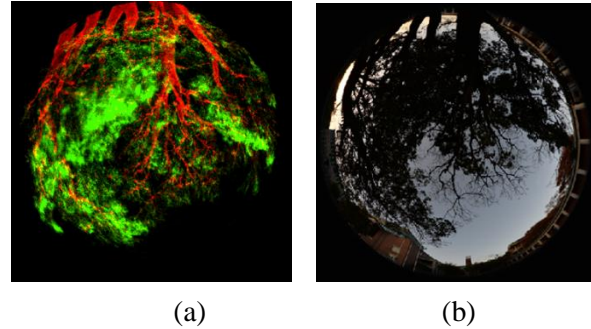


Figure 4.5 Compare virtual hemispherical photograph(a) and hemispherical photograph(b)

### 4.5 Method for calculating the shielding ratio

As a method of calculating the shielding ratio of voxel of leaf, the center position of the sun on the virtual hemispherical photograph at the time of photographing the sun was obtained (Figure 4.6). Next, considering the sun's apparent diameter, the pixel size on the virtual hemispherical photograph was set. Finally, the correlation between the summation of number of leaf voxels on each sun pixel and the brightness value of the photo was calculated. As the result, the shielding ratio of voxel of leaf was 60.3 %, and the shielding ratio of sunlight 60.3 % is assigned to each pixel of the virtual hemispherical photograph as an attribute value

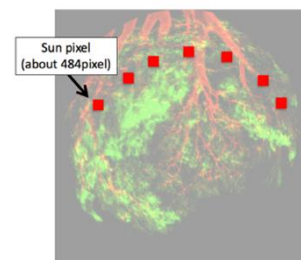


Figure 4.6 Superimposition of virtual hemispherical photograph and solar trajectory

#### 4.6 Estimation result

Solar radiation was estimated using Eq.2 at 10-minute intervals from 8:30 to 16:30 on January 10, 2017 at hemispherical photograph points shown in Figure 4.7. At the same point, the illuminance was observed at 1 second intervals from 8:30 to 16:30 on January 10, 2017. Then, estimated solar radiation and observed illuminance were compared, and result was shown in Figure 4.7. In the estimation result, the peak time and size were different. One reason of the difference is the date of voxelization and the date of illuminance measurement is also different. In addition, the illuminance meter is difficult to directly compare with estimated result because visual sensitivity correction is done.

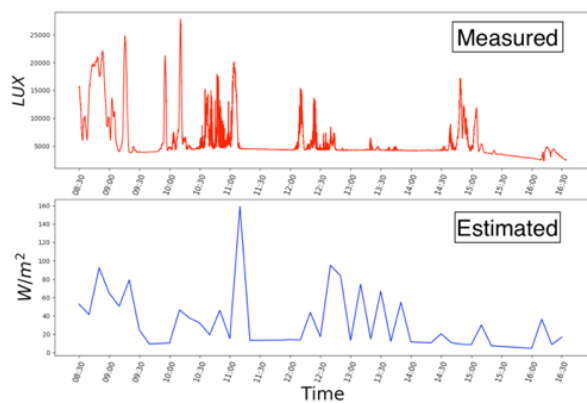


Figure4.7 Comparison of estimated value of solar radiation and illuminance at hemispherical photographing point

#### 5. Conclusions

In this paper, In this paper, The construction method of the voxel model of the forest, and explain how to assign attribute values, such as leaf area, the woody material volume and the leaf shielding ratio. The applications of voxel model were performed to forest environment analysis, such as the estimation of leaf area index (LAI), woody material volume, and solar radiation on the forest floor. The voxel model was applicable in analysis of forest environment.

However, the accuracy verification of LAI, woody material volume and solar radiation from voxel model is not sufficient. As a verification method, some trees will be actually cut down and measure the material volume and LAI. Regarding the estimated solar radiation, solar radiation will be measured at the same time.

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