LiDAR Introduces Revolutionary Changes in Its Approach to Forest Management

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ABSTRACT

The harvesting of timber with a view to the sustainable use of timber resources is called yield regulation. One problem with using this simple indicator is the lack of information it provides for forest management. The first half of this paper will trace how indicators have shifted with time. As a result of looking back on the past, it was confirmed that a simple index was effective for preventing overcutting. The second half of this paper will outline the revolutionary changes introduced by LiDAR. The main findings were as follows. Firstly, because LiDAR has made it possible to measure tree heights, the fundamental data used in forest management will switch from diameter of breast height to tree height in the near future. Secondly, because population data of both trees and ground surface can be obtained through the analysis of LiDAR data, the base unit of forest management will switch from forest stand in nature to forest land artificially separated by squares like a grid. And lastly, because we can obtain both DSM and DTM from LiDAR data, we now have access to precise population data about standing trees and ground surface. This opens up new opportunities to help forest managers in their work. LiDAR has not only brought about a great technical innovation in the field of forest management, but it has also ushered in a major revolution in the philosophy of forest management.

Keyword: forest management, indicator, LiDAR, yield regulation

CHARACTERISTICS OF FOREST MANAGEMENT PHILOSOPHY

The forest is a complex living organism, and is composed of a network of various lifeforms. Furthermore, those living things are constantly changing through interaction with other living things and with the environment around them. Consequently, the overall picture of the activities of the forest has still not been elucidated. It is absolutely impossible for human beings to fully grasp the overall picture of the forest, because the forest is nature itself.

We receive many blessings from the forest. Forests give us water, timber, mushrooms, edible wild plants, scenic spots and much more. It would be impossible to list all the benefits we obtain from our forests. Forests fulfil a variety of functions, including the prevention of global warming, the conservation of biodiversity, the protection of land and soil, the prevention of landslides, and the formation of a pleasant environment. Furthermore, forests are used for activities related to health and recreation. Lastly, forests have a close connection with culture and religion.

Our predecessors, in order to ensure that they could always enjoy the many benefits of forests, made specific rules for the wise management of forest resources, based on knowledge accumulated over time. The various rules governing the sustainable use of timber resources are collectively called yield regulation. There are many yield regulation rules (Tanaka, 1996), and they have evolved over time. It is impossible to regulate all aspects of a forest, because it is a complex living organism; it is nature itself. A forest is not a factory for timber production. Our input can be made through forestry activities such as planting, tending and felling.

Therefore, in forest management, our predecessors had no choice but to use simple indicators to sketch a rough picture of the state of the forest. In other words, because the activities of this complicated living organism could not be perfectly controlled, our predecessors introduced simple indicators for use in forest management. And they decided to increase or decrease the amount of harvest from the forest while confirm-
sustainability of timber resources is given the highest priority through the strict regulation of felling areas.

Indicator Used by the Flachenfachwerksmethode

Regulation of the amount of timber harvested through controlling the area of forest felled is also seen in the Flachenfachwerksmethode. *Flachen* means “area”, and *fachwerksmethode* is a yield regulation method which makes yield or felling area of every implementation period equal.

In 1795, Hartig (Fig. 2) proposed the Massenfachwerksmethode, i.e. volume allocation method, which made the yield of every implementation period equal. However, it was difficult to predict future harvests, because the amount of timber harvested was dependent on the amount of growth. Consequently, there was a possibility of data manipulation, which might lead to overestimating the amount of growth in the Massenfachwerksmethode.

But in 1804, Cotta (Fig. 3) proposed the Flachenfachwerksmethode, i.e. felling area allocation method. Fig. 4 is an image of the Flachenfachwerksmethode. There was no need to worry about data manipulation in this case, because the felling area was strictly limited. The disadvantage of the Flachenfachwerksmethode is that the trend of changes in simple indicator. Consequently, the indicators used in this case must be practical and reliable. Also, they must play an effective role in preventing the occurrence of wrong practices in forest management.

In this paper, some indicators from the main methods of yield regulation have been chosen as research subjects, and we trace how they have shifted with progress in technical innovation and social needs. Then, the future direction of development of both the technology and the philosophy of sustainable forest management are considered. The emphasis is on the new forest management philosophy brought about by the application of LiDAR technology.

THE HISTORY AND THE DEVELOPMENT OF THE PHILOSOPHY OF FOREST MANAGEMENT

Indicator Used by the Schlageinteilungsmethode

The regulations governing the sustainable use of timber resources are collectively called yield regulation, and they play an important role in putting a brake on overcutting. It is said that the oldest yield regulation method is the Schlageinteilungsmethode, that is, the demarcated forestry method. The annual standard felling area prescribed by this method is a block of fixed proportion equal to the total managed forest area ($F$) divided by the number of years of rotation ($u$). So, the size of each block is $F/u$. A similar rule is found all over the world, including Japan. Fig. 1 shows an image which illustrates the Schlageinteilungsmethode. This method is characterized by using as the indicator not the amount of timber harvested, but rather the area of forest harvested. This method specifies a strict felling area for each year. One big advantage of this method is that it makes it difficult for data manipulation to occur, since it uses the area harvested as its indicator. Also, it is easy to identify illegal felling, because the areas are so clearly defined. The obvious disadvantage of this method is fluctuations in the amount of timber harvested annually. However, even with such a drawback, the sustainability of timber resources is given the highest priority through the strict regulation of felling areas.

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Normal growing stock is defined as follows. When the rotation of the Normalwald (normal forest) is $u$ years, and the result of the integration of the growth curve of volume per ha from the starting point to the $u$ is $S$, the normal growing stock per ha is equal to $S$ divided by $u$. Therefore, when we want to know the normal growing stock according to this definition, we must investigate beforehand the actual growing stock of the various forest age groups up to $u$ years. But, this is not an easy thing, because the number of sampling plots in a field survey is at least one hundred. In addition, we need to conduct a field survey for every site class and for every main tree species. Consequently, great efforts are needed to execute such hard work without mistakes.

In case of the Normalvorratsmethode, the amount of annual standard harvest changes depending on the assessment of the normal growing stock. Therefore, there is room for data manipulation. As shown in the equation of the Kameraltaxe, a lower amount of the normal growing stock leads to a larger amount of annual standard harvest.

Here is the equation of the Kameraltaxe:

$$H = G + \frac{(AGS - NGS)}{PI},$$

where $H$ = the amount of annual standard harvest (m$^3$/yr)
$G$ = the amount of annual growth (m$^3$/yr)
$AGS$ = the actual growing stock (m$^3$)
$NGS$ = the normal growing stock (m$^3$)
$PI$ = the period of improvement in growing stock (years).

Our predecessors came up with a nice solution to this problem. They contrived a way of estimating the normal growing stock from the felling results by using a formula for calculating the area of the triangle instead of integrating the volume of the growth curve. Fig. 5 shows an image of the relationship between the growth curve of volume and the triangle. The area of a triangle is the base times the height divided by two. Here, we can estimate the growing stock per hectare of the rotation age $u$ year from the felling results of the forest which was harvested at the rotation age $u$. This is equivalent to the height of the triangle. Next, the length of the rotation age can be approximately confirmed by counting the tree rings of trees felled at the rotation age $u$. The length of the...
rotation age is equivalent to the base of the triangle.

This way, when we estimate the normal growing stock using the formula of the triangle, the factual data of the normal growing stock are the base and the height of the triangle, and they are precise from the felling results. Therefore, there is little room for data manipulation.

The area calculated by the integration of the volume growth curve is obviously different from the area derived by the formula of the triangle. However, the verification of the basic data by a disinterested party is difficult in the former case, but easy in the latter. Consequently, it is possible to say that the method of estimating a normal growing stock using the formula of the triangle gives us a higher reliability for the sustainability of forest management. An important indicator of the Normalvorratsmethode is the normal growing stock estimated using the formula of the triangle.

Indicator Used by the Kontrollmethode

In the second half of the 19th century, various forest problems became serious issues. Clear cutting of large areas provoked disasters in mountainous regions. In addition, afforestation of even aged pure forest stands increased the fragility of ecosystems, because of damage from disease and harmful insects. As these problems became clear, the operations of natural forest management attracted attention. A philosophy of forest management which acts in harmony with nature was formed.

In the various forest operations of natural forest management, it was the Kontrollmethode that was established as the method of yield regulation. The Kontrollmethode, which means check method, was proposed by Biolley in 1890 and established in 1920. For details of the Kontrollmethode, refer to the technical book. The following is the forest management philosophy of the Kontrollmethode.

In the Kontrollmethode, an inventory of the forest was implemented every 6 years, and the diameters of breast height of all trees in a forest compartment were investigated. Tree height was never investigated. Instead of height measurement, the Kontrollmethode used a one-variable volume table called a tariff. The volume estimated by the use of the tariff was described with a measurement unit called a silve. In other words, there was an unreliability in tree height measurement in practical forest management. However, from the viewpoint of forest management philosophy, the Kontrollmethode had two advantages. One was the effort to manage a forest based on the result of forest inventory which was regularly implemented every 6 years. Another lay in trying to grasp the present state of the forest using highly precise information, that is, the measurements of the breast-height diameter of all trees.

At first glance, the Kontrollmethode is recognized as a rough method, because it omits the measurement of tree height. However, Biolley tried to regulate the amount of harvest on the basis of reliable growth data. In principle, he didn’t permit harvest above the amount of growth. For that purpose, it was necessary to construct a practical forest management system which could improve forest management periodically, based on reliable forest inventory data. It was the Kontrollmethode. The indicator of the Kontrollmethode was the amount of growth, expressed in silve. Consequently, the forest management philosophy of the Kontrollmethode is adapted to the management philosophy of our times.

Indicator Needed in Adaptive Forest Management

Today, the need to manage forests adaptively is common knowledge. Because the forest is a complicated living organism and not a timber production factory, it changes with the passage of time. Consequently, the present condition of the forest and the soundness of its ecosystems must be checked periodically. Following that, forest management must be improved according to the situation. That is, the execution of the PDCA cycle. In the case of quantitative checks, various indicators are used.

Many criteria and indicators for sustainable forest management were defined in various parts of the world for each forest type after the Earth Summit in 1992. For example, the criteria and indicators for temperate forests in areas other than Europe were defined by the Montreal Process, in which Japan took part. Moreover, there are forest management certification systems, such as the FSC (Forest Stewardship Council), and various indicators are used in these certifications.

As mentioned above, various indicators are proposed and used. But when adopting an indicator for sustainable forest management, the following points must be considered. To manage a forest appropriately and to make use of all that the forest has to offer sustainably, the indicator must be practical, easy to understand and easy to check. And we must select an indicator which prevents data manipulation.

The history of forest management philosophy shows that our predecessors intentionally used felling area as an indicator instead of volume of harvest, adopted the formula of triangle instead of the integration, and investigated the diameters of all trees at breast height, without taking into account tree height. However, these are the fruits of the past. The limited technology available to our predecessors limited them to making such choices.
Indicators used in forest management change with technical innovation, because innovation makes the impossible possible, and makes complicated procedures simple. So, we have many alternatives for indicators in the age of IT. One technical innovation which has appeared recently in the field of forest measurement is LiDAR.

**OUTCOME OF LiDAR**

LiDAR (light detection and ranging) is a system by which we can acquire highly precise, three-dimensional positional information of features by irradiating laser light from an aircraft to the surface and measuring the reflection of the laser. In a forested area, the first return is mainly reflected from the surface of the tree crown and the last return is mainly reflected from the surface of the ground. Other returns are reflections from tree trunks, branches or leaves of the tree crown.

LiDAR data has started being used in actual forest management in recent years. The data on forests obtained from analyzing LiDAR data can be categorized into the following three main types: data on forest stands, on individual trees, and on the ground surface.

**Data on Forest Stands**

As a basic analysis of LiDAR data, the data of first return is used to create a DSM (digital surface model) and the data of last return to create a DTM (digital terrain model). For forest management, a DSM is used as mesh to show the canopy, while a DTM is used as mesh to show the forest floor. The difference between the DSM and the DTM is called the DCHM (digital canopy height model), and shows the canopy height as a mesh. The DCHM can be considered a kind of representative value of tree height in each mesh, so this data, combined with separately-obtained other data such as the basal area, can be used to create mesh showing the distribution of growing stock.

**Data on Individual Trees**

While it depends on the size and shape of trees, an analysis of LiDAR point cloud data can make it possible to extract individual trees, and to measure their heights, crown widths, and crown lengths (Shiota et al., 2017). Methods proposed for extracting individual trees are Local Maximum Filtering (LMF), watershed algorithms, valley-following algorithms and others.

By using local maximum filtering, treetops can be identified and then height of identified treetop is considered as tree height. The number of treetops makes it possible to know the density of standing trees. The valley-following algorithm considers the gap between crowns as valley and extracts valley cells from DSM or DCHM data. From the extracted valley cells, we can extract canopy polygons. The maximum value within a canopy polygon shows the tree height, while the number of canopy polygons shows the number of standing trees. The area of a canopy polygon can be treated as the canopy projection area. After the above mentioned analysis, it is possible to create a site index distribution map or a tree height distribution map from the height data on individual trees. In addition, from the data of canopy polygon area and tree height, the diameter of breast height and the basal area can be estimated to a certain extent.

If the Fusion/LDV software developed by the USDA Forest Service is used, it is possible to extract the individual tree, depending on its size or shape, and measure its height, crown width, and crown length (Fig. 6).

In this way, analysis of LiDAR point cloud data can allow the collection of data on individual trees (Fig. 7).

**Data on the Ground Surface**

It is possible to create a slope sectional map, an aspect sectional map, and a flow accumulation map (Fig. 8) from DTM. It is also possible to calculate the profiles of longitudinal sections and cross sections. Moreover, if detailed DTM of less than 1 m are used, it is possible to create a CS topographical map (Fig. 9). A CS topographical map is a composite image created by calculating curvature and slope from DTM and assigning specified colors to each thematic map thus obtained (Toda, 2012). Because the image of a CS topographical map looks like a three-dimensional picture, it is possible to visually detect landslides, topography, valley heads, locations of springs, and so on.

By using the CS topographical maps and the thematic maps obtained from DTM, we can identify areas where conservation is required from the perspective of mountainside
LiDAR Data Provides Us with Population Information

As noted above, we manage forests using indicators that are both simple and practical, in order to be able to sustainably nurture and benefit from complex forest ecosystems. These indicators have changed over time, in line with changes in forest management philosophy and technical innovations.

Two of the technologies that most heavily affected economic activity after the Second World War are computers and statistics. Forest management was no exception to this. The development of computers and their applied technologies have both brought about mathematical statistical analytical methods such as LP, GP and multivariate analysis, and also brought about major changes in the fields of forest mensuration and forest management through technologies such as remote sensing and GIS.

On the other hand, statistics are applied to the systematization of forest surveys based on sampling theory. Stratified sampling methods and multi-stage extraction methods are now well established in the field of forest measurement.

Using these two major technologies—computers and statistics—we have constructed a forest management system that uses forest stands as its basic unit. In other words, a forest stand is expressed as polygon in forest GIS, and its attribute data is basically the average or total value estimated from the sampling data.

However, the use of LiDAR data has changed this situation in a revolutionary way. Instead of samples, we can now obtain data for the population of trees that make up the forest stand. In fact, it is now possible to handle population data directly with its location data. There is no need to estimate average values and total volumes. The reality is that there is a very large difference between sample and population. LiDAR changes the basic elements of forest measurement from diameter of breast height to tree height, and allows surveying of tree heights for each tree, thus making it possible to provide...
very accurate data on populations. LiDAR has brought about a revolution in the field of forest management.

FROM FOREST MANAGEMENT USING FOREST STANDS AS UNITS TO LAND USE MANAGEMENT USING MESHES AS UNITS

Analysis of LiDAR data has opened up new doors for the field of forest management, especially from the forest stand level to the individual tree level, and from diameter of breast height to tree height. However, there is still room for further improvement in the application of this technology, and it will take a bit more time until it has been made practical for forest management work. That said, DSM and DTM created from LiDAR data are already sufficiently precise for practical work. Therefore, this section will consider forest management units made by these meshes.

As noted earlier, the advent of LiDAR means that it is now possible to obtain data on populations themselves. In some cases, it is even possible to obtain data on individual trees. This means that there is less need to summarize population data for each mesh unit into a forest stand unit. When managing forests, it is more natural to treat population data as it is.

In forest management which uses standing trees as its basic unit, there are a lot of data related to these trees, so that means that the database inevitably ends up being mostly forest status data. In addition, forests are composed of standing trees and forest land to begin with, so the information about the site conditions is needed as well. Consequently, when we consider forest management that uses zones divided up by DTM meshes as its basic unit (Fig. 10), it is recommended to position forest management as part of land use management.

When meshes are used as the basic unit of forest management, there is the problem of just how big to make the meshes. The following two perspectives are important when it comes to solving this issue.

One is that, when surveying a forest, you need to be able to confirm which mesh you are in while on site. This problem depends on the positioning accuracy of GNSS. In other words, the higher the GNSS positioning accuracy, the smaller the meshes can be. The other perspective is that, when managing standing trees, you need to know what size mesh is appropriate. Meshes that are smaller than the tree crown area cannot fulfill their purpose. In addition, meshes that are too small are meaningless when it comes to calculating slopes or aspects from meshes.

Hypothetically, if there are 625 trees per hectare, then their average spacing is 4 m. If there are 400 trees per hectare, then their average spacing becomes 5 m. Therefore, a good figure for the minimum mesh size would be an area of 5 m square. However, we can assume that the effects of a single tree on its surroundings, at least as an estimate, extend for a distance proportional to its height and thus we need zones with a radius of 25 m around the tree. Therefore, the maximum size of a mesh would be, in nice round figures, a square 50 m on a side. Looking at it in this way, we obtain mesh sizes from 5 to 50 m on a side.

The positioning accuracy of the portable GNSS that is often used in forest surveys is about 4 m. If we set up a circular plot of 0.02 ha, or a circle with a radius of 7.98 m, centered around the GNSS positioning point, then the size of a mesh large enough to include this circle is calculated as follows. Because the circular plot’s center may shift by 4 m, the size of a mesh within which the circular plot would remain is about 24 m (= (4 + 7.98) × 2). These considerations suggest that a good round size for mesh size is a square 25 m on a side (Fig. 11).

THE REVOLUTION BROUGHT ABOUT BY LiDAR DATA

Because we couldn’t investigate forest ecosystems perfectly, our predecessors managed forests using simple indicators which could grasp the overall forest intuitively in conditions of insufficient information. These indicators were the felling area, the normal growing stock, which was calculated from simple formulae, and the ‘silve’ which was the unit of wood volume estimated by using a simple one-variable volume table. Also, the data that forestry books used was the values derived from yield Tables or statistics values (the average, the total amount volume and so on) which were estimated from the sampling data.

The advent of LiDAR has totally changed forest management. In some cases, LiDAR makes the measurement of tree height possible. Therefore, the fundamental data of forest
The biggest environmental issue of the 21st century is to mitigate climate change. Forests are not just for producing timber, they play a vital role in absorbing carbon dioxide, a greenhouse gas, as well as in reducing mountain disasters caused by freak weather patterns brought about by climate change. Under these conditions, we need to change forest management from timber production to a forest management that includes land use management suited for adaptation to climate change.

Until now, forest planners have played a role in preventing overcutting. However, with the advent of LiDAR, there is now more weight on their shoulders. They have bigger responsibilities as managers of forests, because the management of both forests and land based on monitoring is both indispensable and always evolving.

LiDAR has not only brought about a great technical innovation in the field of forest management, but has also brought about a major revolution in the awareness of forest managers, that is, in the philosophy of forest management.

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