Analysis and Comparison of Methods for Determining Small Piles of Wood Chips Using Laser Scanning Technology

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The monitoring of forest biomass stock volumes in larger operations is typically conducted irregularly, either by tracking cargo arrivals or by using simple manual measurement methods. The objective of this study was to assess the accuracy of smart methods based on laser scanning technology, integrated into mobile phones and a handheld laser scanner, for measuring smaller piles of forest chips. For the experiment, a total of 50 m³ of fiberwood logs were chipped and distributed into four piles. The smart solutions selected for laser scanning of forest biomass in this study were the Stonex Geoslam X120 GO handheld laser scanner and the iPhone 14 Pro Max equipped with a LiDAR sensor. The results were influenced by the selected conversion coefficient and the exclusion of small scattered fragments of forest chips around the piles, which were not included in the final volume calculation. The smallest discrepancy identified by the smart solutions was 3 m³ (6%) of woody mass. The findings demonstrated that the smart solutions utilizing LiDAR technology offer good affordability, ease of use, and satisfactory accuracy. They are user-friendly and provide quick results.

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INTRODUCTION

The increasing demand for renewable energy sources derived from forest biomass, coupled with the construction of new energy facilities using it as a primary energy source, introduces new technological challenges. These challenges primarily involve optimizing the logistics chain, ensuring supply efficiency, and accurately determining volume (or weight) at each production phase (Lewandowski 2015; Garcia *et al.* 2018). Over the past 15 years, there has also been significant development in precision forestry and close-range methods. These methods incorporate tools such as geographic information systems (GIS), global positioning systems (GPS), laser imaging, detection and ranging (LiDAR) applications, unmanned aerial vehicles (UAVs), and other technologies. These methods are widely used to gather data related to forest stands and quantify their parameters (Kovácsová and Antalová 2010; dos Santos 2017; Woo *et al.* 2019).

The use of these methods increasingly accelerates and enhances the acquisition and evaluation of data on forest stand growth and biomass stocks. This improves the efficiency of forest stand management and provides more detailed information for the sustainable utilization of forest resources. As the emphasis on responsible natural resource use, environmental protection, and global climate change continues to grow, the significance of these methods is becoming even more pronounced (Pascual *et al.* 2016; Latterini *et al.* 2022; Sofia *et al.* 2022; Xiang *et al.* 2024).

Forest biomass is a highly variable material in terms of shape and weight due to its non-uniform nature. This variability stems from its biological origins and the differing properties of individual tree species, growth patterns, regional conditions, forest management practices, and numerous other factors. As a result, precise quantification during various growth and production phases is challenging, and the quantitative parameters of the same tree can vary at different stages of the logistics process. However, accurate biomass quantification is essential from economic, ecological, and production-technical perspectives (Song *et al.* 2023; Pinagé *et al.* 2023; Li *et al.* 2024).

In addition to standard dendrometric procedures for determining the volume or weight of forest biomass, digital photogrammetry, laser scanning methods, and unmanned aerial vehicles (drones) have seen significant advancements in recent years. These modern methods offer clear advantages, including higher accuracy, lower costs, reduced personnel requirements, and greater flexibility and efficiency (Saarinen *et al.* 2017; Demol *et al.* 2022). The imaging and resolution capabilities of precision forestry techniques have also improved considerably. However, most existing methods are focused on analyzing biomass that remains unharvested and grows in forest stands. These methods were primarily developed to estimate the quantitative parameters of standing trees, assess their health by mapping the condition of assimilation organs and analyzing tree crowns, and automate the identification of tree species and their height growth (Ferrarese *et al.* 2015; Shendryk *et al.* 2016; Paris *et al.* 2017; Sedliak *et al.* 2019; Fraser and Congalton 2019).

However, a wide range of precision forestry methods can also be applied to quantify tree biomass or harvested logs (Ducey and Astrup 2018; Brede *et al.* 2019; Borz and Proto 2022; Lu and Jiang 2024). The use of laser scanning methods for determining wood pile volumes can provide accuracy comparable to classic dendrometric procedures (such as cubic formulas, thickness and length measurements, and conversion coefficients). However, this accuracy depends on the specific method used and, significantly, on the size of the wood stack (Purfürst *et al.* 2023).

The operation of heating plants and power plants that use forest biomass as their primary raw material necessitates the creation of larger stockpiles and an optimized logistics network. These facilities often experience continuous supply and withdrawal of raw materials (Gejdoš *et al.* 2018). However, forest biomass typically lacks uniform size parameters and is sourced from different types of trees and multiple suppliers (Kimming *et al.* 2011). As a result, in larger operations, current stock records are usually maintained irregularly through cargo arrival logs or manual measurements using tape measures (Lieskovský and Gejdoš 2023). Accurate real-time recordkeeping or immediate detection within a short time frame—without the need for additional software evaluation—presents a significant technological challenge, especially when dealing with large volumes. Biomass production often occurs directly in forest stands, creating a demand for quick and accurate volume determination of the supplied materials for customers right at the collection point. Unmanned aerial vehicles (UAVs) have been employed for these purposes with relative success; however, they require additional software analysis and considerable operator experience (Mokroš *et al.* 2016). In the last five years, small mobile devices, such as phones and tablets, have been equipped with laser scanning (LiDAR) sensors and application solutions for volume scanning. These devices have been successfully tested for determining the quantitative parameters of standing trees as well as assessing the volume of piles of disintegrated materials (Gollob *et al.* 2021; Hulanová *et al.* 2024; Apafaian *et* *al.* 2024).

The present study compared simple laser scanning methods using a mobile phone with a LiDAR scanner and applications, as well as a handheld laser scanner, on smaller piles of forest chips. The objective was to establish a new methodology for these devices, evaluate existing application solutions, and assess the effectiveness of these smart solutions. The results are intended to enhance the efficiency and accuracy of forestry enterprises in operational and business relationships, particularly in the registration of disintegrated forest biomass. Additionally, they aim to expand the possibilities for optimizing logistic solutions. This will facilitate more effective management and recording of available forest biomass resources.

EXPERIMENTAL

Location and Material

The experiment was conducted within the Ligno-Silva scientific research area of the National Forestry Center in Slovakia, located in the Banská Bystrica self-governing region in central Slovakia (Fig. 1).

Fig. 1. Location of the experimental measurement

Beech wood (*Fagus sylvatica*) was selected for the experiment, specifically from the quality class of fiber and industrial wood. The wood was sourced from the same location and forest stand of the University Forestry Enterprise at the Technical University in Zvolen.

A total of 50 m³ of beech fiber wood, harvested in May 2023, was brought to the experimental site. The wood was subsequently chipped using a Biber 84 mobile chipper on May 23, 2024. The chipped biomass was arranged into four needle-shaped piles, each with a base measuring 4x4 m and a height of 2 m (Fig. 2). The piles were loosely packed, and the entire 50 m³ of fiber wood was chipped without any residue; no material was added or removed. The piles were created directly on the soil surface without a base layer. Part of the storage area was situated on a slope, but the height difference from the base layer to the bottom edge of the piles did not exceed 1 meter. This height difference was georeferenced and accounted for using a software solution.

Fig. 2. Preparation of the experimental piles with chipper

Measuring Equipment and Software Evaluation

The following smart solutions for laser scanning forest biomass were selected for this work: the Stonex Geoslam X120 GO handheld laser scanner (Fig. 3) and the iPhone 14 Pro Max equipped with a LiDAR sensor. The laser scan point cloud data was processed using CloudCompare and GOpost software. Additionally, the free “3D Scanner App” was utilized to process the scanned data from the iPhone.

Fig. 3. Laser scanner Stonex Geoslam X120 GO

To georeference the data in CloudCompare software, the exact positions of fixed points on both sides of the piles were marked and focused with a tape measure, resulting in a total of eight marked points—one fixed point on each side of every pile (Fig. 4). These focused points, along with the laser scanning of the surrounding terrain, allowed for the consideration of terrain irregularities when evaluating the volume of the piles, as some piles were situated on a slight slope rather than on a level surface. The point cloud generated using the Geoslam handheld scanner was georeferenced in the local coordinate system, with the zero Z-coordinate positioned above ground level. Therefore, to accurately calculate the volume of the piles, it was necessary to add the volume above the zero height (positive Z-coordinates) to the volume below zero height (negative Z-coordinates). Scanned parts that did not represent the mass of woody biomass (such as assimilative organs of surrounding vegetation, rubble, and gravel from the subsoil beneath the piles) were manually filtered out of the point cloud in the GOpost software. Following this cleaning process, the volume of the piles was subsequently calculated in CloudCompare.

Fig. 4. Placement of the points on piles for georeferencing positions

Due to the operational limitations of the iPhone 14 Pro Max, which has restricted memory capacity, detailed scanning of larger volumes of piles resulted in significant error rates, application freezes, and device overheating in higher temperatures. Consequently, each pile was scanned separately (Fig. 5). Scanning was conducted using the 3D Scanner App, which is available for free in the App Store. The boundaries between individual piles were determined using reference targets (Fig. 4), which were positioned with the help of GPS.

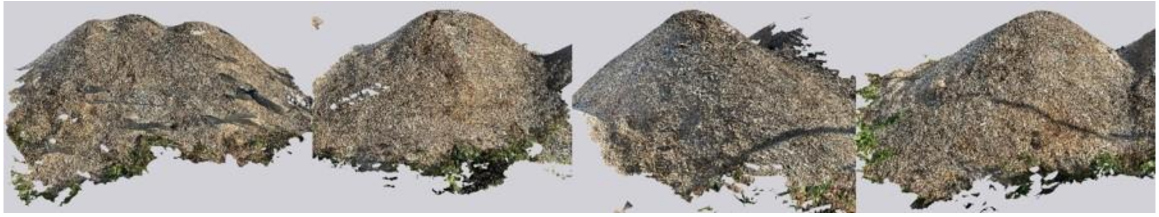

Fig. 5. LiDAR scans of piles in the 3d Scanner App performed by iPhone 14 Pro Max

The evaluation of the total volume of the scanned piles was also conducted within this application.

The actual scanning and evaluation process took place on August 6, 2024, less than three months after the chipping process. This approach more accurately reflects operational conditions, as the volumes of biomass piles are typically not measured immediately after their creation, but rather after some time has elapsed, allowing the biomass to settle and compact. However, this delay can influence the resulting accuracy of the determined volume of wood in the pile to some extent. Atmospheric factors can cause some biomass to fall from the uniform shape of the piles into the surrounding area.

A stacked cubic meter always represents a certain volume of wood and air. Therefore, conversion coefficients are used when converting to solid cubic meters. These coefficients typically depend on regional or national technical conditions, which are outlined in national technical standards. When measuring wood chips by volume, common units of measurement include stacked meter (rm), bulk stacked meter (sqm), cubic meter (m^3), or tons (t). For the conversion from loose stacked meters, the conversion coefficients specified in STN 48 0057 Assortments of Wood, as well as those from the Austrian customs in the wood trade (ATTP) (ÖHU 2007), were utilized. A summary of the conversion coefficients used to convert stacked cubic meters to solid cubic meters (m^3) of wood is provided in Table 1.

Table 1. Conversion Coefficients for Wood Chips from Stacked Volume to Volume in Solid Cubic Meters According to Slovakian and Austrian Technical Standards

Standard	Wood Chips Technical Quality	Stacked Volume of Wood Chips	Volume in Solid Cubic Meter (m^3)
1. STN 48 0057	Chips for mechanical and chemical purposes and fine-grained energy wood chips	1	0.41
2. STN 48 0057	Coarse grained energy wood	1	0.45
3. ATTP	Fine grained energy wood chips (fraction max. 30 mm)	1	0.40
4. ATTP	Medium grained energy wood chips (fraction max. 50 mm)	1	0.33

RESULTS AND DISCUSSION

The detected volume was evaluated and recalculated using two manual methods based on LiDAR technology. These methods are generally simple and can be operated by personnel with minimal training after a brief instruction. They allow for the determination of the volume of disintegrated forest biomass in the form of forest chips, provided it is not in large-capacity storage. Notably, the method of utilizing a mobile phone with an existing application solution is easier to use and faster. With this method, results (scanning plus processing in the application) can be obtained within 30 min. In contrast, using the Stonex Geoslam X120 GO handheld scanner necessitates exporting the scanned data to a computer for processing in up to two different software applications. This step includes filtering out unwanted data and evaluating the results, which requires more detailed instruction and user experience. The total time for scanning, processing, and evaluating the results was approximately 1.5 h, which is up to three times longer than the mobile phone method. Additionally, the purchase price of the Stonex Geoslam X120 GO scanner, along with the necessary software, can exceed that of a mobile phone with a LiDAR sensor by as much as ten times. Therefore, in terms of economic efficiency and user comfort, the approach to using a mobile phone is significantly superior to that of a handheld laser scanner.

Figure 6 illustrates the output of the laser scan point cloud evaluation conducted using the Stonex handheld scanner. The figure displays the assessment of the height levels of individual piles, along with the referencing of height differences in areas where the base layer beneath the piles was uneven and situated on a slight slope. From this digital model representing the distribution and levels of the chip piles, the software calculated the total volume at 85.769 stacked m³. The volume below the terrain level, where part of the pile was located on a slope, was added (18.742 stacked m³). Consequently, the total calculated volume of all piles using this method was 104.511 stacked m³. It is important to note that some biomass in the form of forest chips was scattered in smaller fragments near the piles, and the volume of this scattered biomass was not included in the total volume calculation.

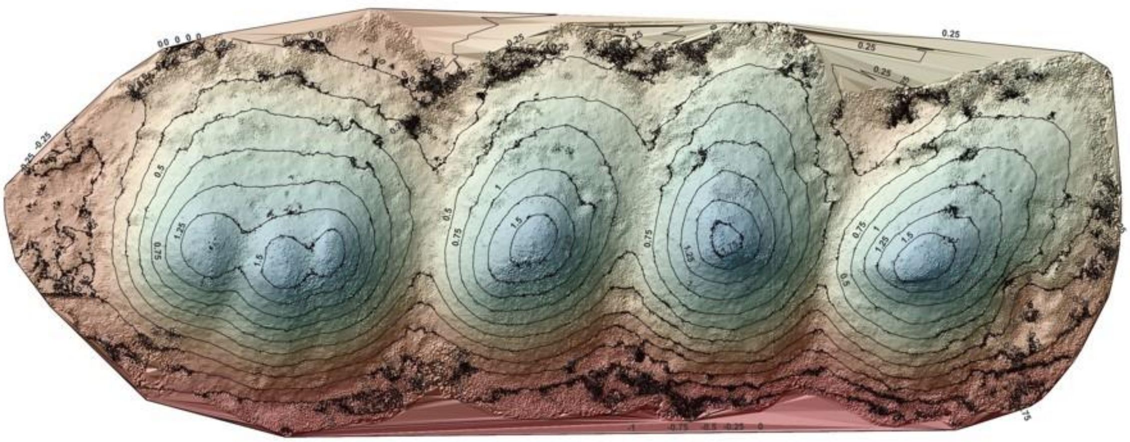

Fig. 6. Processed LiDAR scan from a handheld STONEX laser scanner with determination of height levels and exact positions

Figure 7 presents a summary of the results from the manual evaluation of the scan conducted using the iPhone, processed through the 3D Scanner App. The evaluation involved manually referencing the boundaries of the piles from the scans depicted in Fig. 5. The boundaries were determined using reference targets (Fig. 4), which were positioned with the help of GPS module. The volume of each pile was calculated separately.

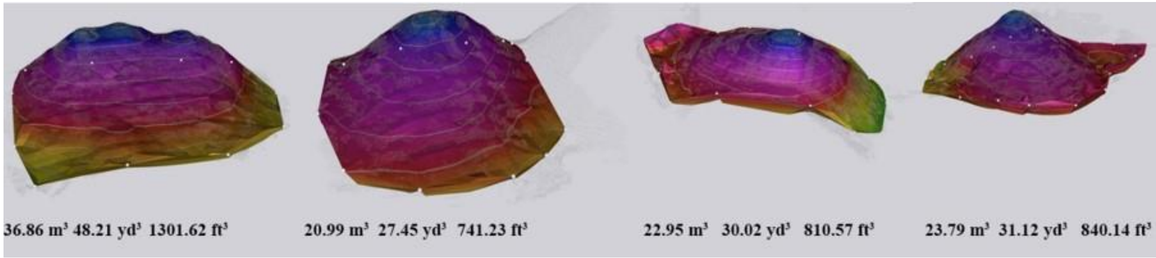

Fig. 7. Processed LiDAR scan from iPhone 14 Pro Max with determination of volume (performed in 3d Scanner App)

Overall, the application calculated the volume of the piles to be 104.59 stacked m³, which is nearly identical to the result obtained using the handheld laser scanner evaluated in specialized software.

At the start of the experiment, 50 m³ of fiber and industrial wood, sourced from 4-meter long logs, was chipped. The volume values were then determined using the smart laser scanning methods employed in the study. These values were converted from bulk-stacked cubic meters to solid cubic meters of wood using the conversion coefficients listed in Table 1. The results of the assessment of the detected converted volume are presented in Table 2.

The results indicated that the analysis using both methods yielded nearly identical outcomes. The findings were also significantly influenced by the conversion coefficient employed. The most accurate results were obtained using the conversion coefficient for coarse-grained energy chips according to STN 48 0057, set at 0.45 m^3 for every 1 m^3 of loose chips. This approach resulted in a discrepancy of only 6% between the volume of wood processed during chipping and the volume found in the piles. When evaluating these differences, it is important to consider that certain losses occur during the chipping process. Some biomass is ground into dust, some remains in the technological components of the chipper, and some is freely scattered on the storage surface rather than deposited in the pile layers. These losses also contribute to the discrepancy not detected in the piles. Additionally, some wood loss may be attributed to the scanning and evaluation processes, which are partially limited by the capabilities of mobile phones and software.

Table 2. Volume Calculation in Solid Cubic Meters of Wood According to Conversion Coefficients

Method	Used Conversion Coefficient, according to Table 1	Measured Volume by Smart LiDAR	Total Volume in Solid Cubic Meters (m^3)	Percentage Deviation from Reference Value 50 m^3 of Solid Wood (%)
iPhone	1	104.59	42.8	14.4
	2		47.0	6
	3		41.8	16.4
	4		34.5	31
Stonex Geoslam X120 GO	1	104.511	42.8	14.4
	2		47.0	6
	3		41.8	16.4
	4		34.4	33.2

The results also demonstrated that when detecting and calculating the volume of small piles of forest chips, mobile applications and the LiDAR sensors integrated into mobile phones provide relatively accurate and satisfactory results, suitable for forestry operations. This approach and methodological solution are particularly useful for inventorying small volumes of forest biomass.

So far, these methods and approaches have primarily been employed to determine the quantitative parameters (especially thickness) of standing trees or extracted trunks (Itakura *et al.* 2017; Jayathunga *et al.* 2018). Current forestry operations largely rely on standard dendrometric and taxing procedures for determining and recording the quantities of produced assortments of raw wood and forest biomass. The volume of forest chip piles is mostly assessed based on wood type and relative humidity, particularly using conversion coefficients defined at the national level within the framework of technical standards (Jakubovski and Praczyk 2022). Operational practices have shown that a quick and accurate assessment of the current volume of biomass in large-capacity piles can be achieved without demanding significant instrumentation or higher expertise from personnel. Drone technology has been proven to provide relatively high accuracy for these purposes. When utilizing specialized software, the volume determined by this method deviated by only 2.6% from the actual value (Matsimbe *et al.* 2022). Mokroš *et al.* (2016) found that using GNSS-based devices, combined with appropriate software, can reduce the time required to determine the volume of a large-capacity chip pile by 12 to 20 times compared to drone technology. The differences in volume determined by UAV and GNSS methods ranged from 7.9% to 12%, which, when compared to the smart LiDAR approaches, can represent a difference of up to twice the actual volume. However, this approach necessitates professionally qualified personnel and incurs relatively high investment costs for instrumentation and software. Similarly high accuracy in determining the volume of chip piles has also been observed using drone technology with differential models like "structure from motion," where the deviation of the calculated volume from the real state ranged from 1% to 3% (Mund *et al.* 2017).

One of the challenges of using laser scanning methods for wood chips is the significant diversity and variety in the size fractions of the solid material. In contrast, when laser scanning homogeneous mineral raw materials, studies have shown that the differences between the actual volume and the volume detected using a terrestrial LiDAR scanner are only 0.8% (Zhang *et al.* 2020). However, the use of a terrestrial scanner involves a much higher initial investment, which can be excessive considering the primary purpose of detecting biomass volume in the field. Some authors suggest that UAVs may be a more suitable method for determining the volume of biomass piles (Lawrence and Letham 2018). While UAVs offer a more cost-effective solution, they also present challenges in field conditions, particularly regarding the expertise required for operation, software needs, and time efficiency. Piloting a drone necessitates specific skills, and in some countries, obtaining the appropriate certifications and authorizations is mandatory. Additionally, the shape and volume of stored biomass piles can change frequently during operation, complicating their rapid deployment and effective use (Liu *et al.* 2020a).

An approach utilizing multiple mathematical algorithms can also yield relatively accurate results in this area. For instance, when applying these algorithms to calculate the volume of agricultural products such as buckwheat and corn stored in piles, the relative error of the determined volume was found to be below 5% (Liu *et al*. 2020b).

Based on the analysis of available literature and the results, the choice of method for determining the volume of forest chips is influenced by several key factors: accuracy, speed, ease of operation, and the cost of necessary equipment. The findings indicate that even less expensive laser scanning solutions can provide satisfactorily accurate results for measuring volume in smaller piles. Specifically, solutions that utilize mobile phones equipped with affordable applications represent a relatively fast and accurate approach for determining smaller volumes of biomass in forestry operations.

CONCLUSIONS

1. The results indicate that even cost-effective solutions utilizing laser scanning can yield satisfactorily accurate results when determining the volume of smaller biomass piles. Compared to the standard method of determining wood volume based on the middle thickness and length of the logs, cubic formulas provide a suitable alternative with comparable accuracy. However, their precision also depends on the conversion coefficients used for disintegrated wood.

2. The accuracy of the results is influenced by several factors, including the density of biomass within the layers of the pile, the dispersion of smaller fractions around the pile, and the subjective aspects of the evaluation by the person conducting the scanning and assessment.
3. In practice, there is frequently a continuous withdrawal of biomass alongside the supply of fresh raw material. Therefore, a quick and easily deployable solution is essential for timely and accurate stock volume assessments. Fast and accurate measurement of biomass pile volume is crucial for optimizing logistics in forestry operations and the processing industry.
4. The analyzed smart solutions leveraging laser imaging, detection, and ranging (LiDAR) scanning technology provide a balance of affordability, user-friendliness, and satisfactory accuracy for forestry applications.

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