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Agroforestry Harvesting Residue: A Case Study in Private Forests in Probolinggo, East Java, Indonesia

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ABSTRACT

One of the wood sources in Indonesia is derived from private forests managed with agroforestry systems. The harvesting operation in these forests will produce harvesting residues. The study aimed to quantify the harvesting residue volume and to construct a prediction model for harvesting residue volume in a private forest managed with an agroforestry system. The study was conducted in a private forest managed with an agroforestry system in Probolinggo, East Java. The method employed for quantifying harvesting residue was a whole-tree method. The harvesting residue was classified into stumps, butt ends, top logs, and branches. Harvesting residues with dbh ≥ 4 cm were measured after harvesting. The best model was selected based on the Root Mean Squared Error and the adjusted coefficient of determination values. The number of sample trees was 31 trees, which were chosen by farmers to be felled. The study found that the harvesting residues were 6% of the total harvested volume. The harvesting residue was predominantly the stumps. The best model for estimating harvesting residue volume in agroforestry private forests was $V = 0.042VolTot^{1.248}$. The study concluded that harvesting operations in private forests managed with agroforestry systems produced a small number of harvesting residues. The harvested volume was the most significant indicator for estimating the harvesting residue volume.

1. Introduction

According to Indonesia Regulation Number 41 of 1999, a private forest is defined as a forested area established and managed on privately owned land. The total area of private forests in Indonesia in 2020 was recorded at 20% of the total forest area (approximately 25.2 million ha) (CSBI 2020). In Indonesia, the private forest encompasses three distinct categories, namely monoculture forest, mixed forest, and agroforestry (Aminah et al. 2013; Herwanti 2015; Siarudin et al. 2022; Widiarti and Prajadinata 2008). The most frequently cultivated species in private forests include sengon (*Paraserianthes falcataria*) (Sari et al. 2018; Wijayanto and Briliawan 2022; Wijayanto and Tsaniya 2022; Zulkarnaen 2020), pine (*Pinus merkusii*) (Anjarsari et al. 2022), mahogany (*Swietenia macrophylla*) (Raharjo et al. 2016), teak (*Tectona grandis*) (Anjarsari et al. 2022; Budiaman and Komalasari 2012), gmelina (*Gmelina arborea*) (Sukadaryati et al. 2018), sungkai (*Peronema canescen*) (Wahyudi et al. 2018), and pulai (*Alstonia scholaris*) (Wijaya et al. 2016).

The potential of woods derived from private forests in Indonesia shows variability depending on site characteristics, planting systems, silvicultural practices, and the timber species cultivated. The range of tree diameters that are harvested in private forests varies from 10 to 70 cm. Notably, the average diameter for mahogany was 30 cm, while for pine, it was approximately 20 cm, as reported by Budiningsih et al. (2019) and Anjarsari et al. (2022). The wood production volume in Indonesia has been reported to range from 15.7 m^3/ha to 266 m^3/ha in mixed-forest areas, while in agroforestry systems, it can reach up to 61 m^3/ha. Monoculture forests in Indonesia have been found to yield approximately 275 m^3/ha (Siadari et al. 2013; Soendjoto et al. 2008; Wahyudi et al. 2018).

The phrase "harvest to meet needs" is frequently employed within the context of private forests regarding the rationale for harvesting activities forest farmers undertake. These activities typically occur when the farmers require funds to address unforeseen emergencies or important concerns. The harvesting process can be conducted using either a selective-cutting system or a clear-cutting system (Achmad and Diniyati 2015; Hamdani et al. 2015), depending on factors such as the quantity of demand, the number and size of trees, and the prevailing market conditions. In the context of the present study, it is observed that most of the harvesting activities are carried out by the buyer or a designated harvesting contractor (Abbas et al. 2021). The woods obtained from private forests often show characteristics of short length and low wood quality (Pandit et al. 2011).

Logs derived from private forests serve as a primary wood resource for the small-scale sawmill sector (Syah et al. 2018; Utama et al. 2019). Furthermore, it has been observed that logs derived from sengon (Hidayat et al. 2017; Utama et al. 2019) are frequently employed in many sectors, such as the bare core industry, plywood manufacturing, laminated veneer lumber production, and container industry. The harvesting residue, which is a byproduct of harvesting operations, plays a significant part in the practice of sustainable forest management. Harvesting residues have been identified as significantly impacting tree growth (Helmisaari et al. 2011) and preserving forest biodiversity (Ranius et al. 2018). In addition, it functions as a significant biomass resource (Osman et al. 2014; Vance et al. 2018; Zamora-Cristales and Sessions 2016) and acts as an indicator for evaluating the efficiency of forest harvesting operations (Matangaran and Anggoro 2012; Sukadaryati and Dulsalam 2018). Additionally, it should be noted that harvesting residues significantly preserves forest carbon stock and the nitrogen cycle (Martin et al. 2015; Osone et al. 2015; Smolander et al. 2015). In the global warming phenomenon context, Mills et al. (2023) have documented that the harvesting residues resulting from forest harvesting operations contribute to carbon emissions for a minimum duration of 10 years after the harvesting activity.

The implementation of private forest management in Indonesia has been undertaken extensively since the early 1960s, coinciding with several reforestation and land rehabilitation initiatives throughout the five-year development plans of the New Order era (Utari 2012). Nevertheless, up until now, there has been a noticeable dearth of information on agroforestry practices. One aspect is the information on harvesting residues resulting from harvesting operations. Many studies on harvesting residues in Indonesia have been conducted in large-scale plantation forests (Andini et al. 2017; Budiaman et al. 2016). Additionally, similar observations have been undertaken in natural forest concessions (Budiaman et al. 2020; Budiaman and Audia 2022; Muhdi et al. 2016). However, there is a scarcity of research on harvesting residues in private forests managed with agroforestry systems. A study by Budiaman and Komalasari (2012) examined the leftover logs in private forests managed with agroforestry systems, where the cultivated timber species were teak. Dalya et al. (2021) studied to investigate the form and the characteristics of harvesting residues in teak private forests managed with agroforestry systems. Regrettably, the investigation did not encompass the computation of residual volume. The consideration of potential harvesting residue holds significance in sustainable forest management regarding environmental concerns (Mills et al. 2023; Vance et al. 2018).

Information on the potential of harvesting residues has been obtained through direct measurements in the field. The study into the development of a residual volume model derived from harvesting activities remains mostly unexplored and constrained in its scope. The estimation of tree volume is commonly undertaken practice to determine the potential and economic benefits of forests. The calculation of tree volume can be accomplished by using a volume equation or a tree volume model. A tree volume model is constructed by employing regression analysis to establish a correlation between the diameter and height of a tree. Several tree volume models have been established in various types of forests, including natural forest concessions, plantation forests, and private forests managed with agroforestry systems (Almulqu et al. 2023; Ardelina et al. 2015; Lima et al. 2021; Sumadi et al. 2010; Susanty and Abdurrachman 2016; Qirom and Supriyadi 2012). Furthermore, researchers have also devised tree volume models to assess the volume of forest biomass and carbon (Achmad et al. 2015; Heru et al. 2009), as well as forest stand biomass (Tiryana et al. 2021).

2. Materials and Methods

2.1. Study Site and Time

The study is situated within a private forest managed with an agroforestry system, which is owned by forest farmers affiliated with the cooperative known as Koperasi Alas Mandiri in Probolinggo, East Java. The management of this forest is facilitated through a cooperative agreement with PT Kutai Timber Indonesia (KTI) in Probolinggo. The study site is in Roto Village, Krucil Sub-District, Probolinggo Regency, East Java Province. The research focused on an area of 0.59 ha, employing a "harvest to meet needs" system. The private forest farmer will cut down some trees according to the required funds. This cutting system is called "harvest to meet needs" (locally known as "*tebang butuh*"). The tree species to be cut was sengon. The number of trees cut down by farmers was 31, and they were 5 years old. These trees were sampled in this study. The study was conducted between January and March 2023.

2.2. Data Collection

Measurements of the diameter at breast height (dbh), clear bole, and total height of the standing trees before harvesting were taken. The harvesting operation was carried out by a local harvesting contractor utilizing a chainsaw (Maestro Plus CS6500L, China). The chainsaw possessed a capacity of 55 cc, weighed 10 kg, and had a bar length of 52 cm. Directional felling was applied in the study area by creating a felling notch and pulling with a rope. The felling notch consists of a back cut and notch base without a notch roof. Tree pulling was carried out by two forest workers. Following the bucking procedure, data on the diameter and length of the upper section of the tree were gathered until the small end diameter under the bark (SEDub) attained a value of 4 cm. The selection of the limit for the small end diameter was determined by referring to the small end diameter values specified in the mixed species (locally known as "*kayu rimba*") volume table outlined in the Indonesian National Standard (SNI) number 7533.2.2011 (BSN 2011).

2.3. Quantifying Method of Harvesting Residues

The method employed in this study for quantifying harvesting residue is a whole-tree method. The method identified and quantified the various harvesting residues originating from the individual trees felled. Besides determining the quantity of harvesting residues, this method will also give detailed information on the type of residues available (Budiaman et al. 2020; Tai and Jaeger 1999). The method involved the measurement of log dimensions (diameter and length) of the felled trees. The logs were divided into five classes, namely usable logs (UL), stumps (ST), butt end (BE), top logs (TP), and branches (BRC) (**Table 1** and **Fig. 1**).

Table 1. The type of logs from the harvesting operation

Type of logs	Description
Usable logs	The logs are log sections that meet the specified criteria of the wood industry and are removed from the forest by harvesting contractor
Stumps	The lower part of a tree, which is located under the felling cut and left in the ground
Butt ends	Part of the main logs contains defects, and it must be cut and separated from a usable log
Top logs	Part of the felled tree located above the first branch until a small end diameter of 4 cm
Branches	The logs are part of the tree crown that has diameter of ≥ 4 cm

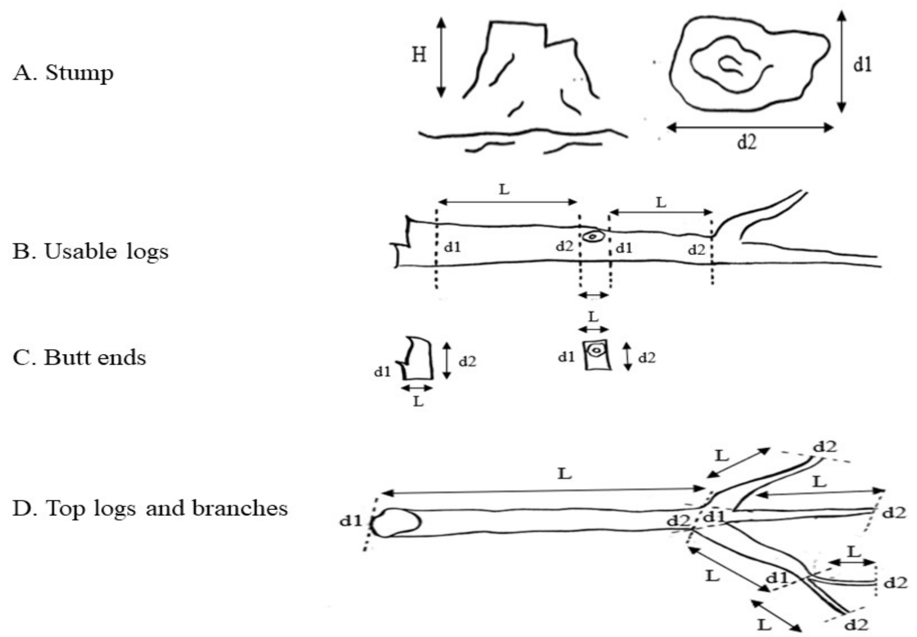

Fig. 1. Classification of logs and the method of diameter and length measurement (Tai and Jaeger 1999).

After the bucking operation, the logs were categorized into two groups: usable (merchantable logs) and harvesting residues. The usable logs are log sections that meet the specified criteria of the wood industry and are removed from the forest by the harvesting contractor (**Table 2**). On the other hand, the harvesting residues are log sections that do not meet the dimensional specifications set by the wood industry until the SEDub reaches a threshold of 4 cm. The utilization factor compares the volume of usable logs divided by the total volume of the felled trees. Meanwhile, the residue factor is defined as the volume of harvesting residues divided by the total volume of the felled trees.

Table 2. Logs specification determined by the wood processing industry in Probolinggo (KTI 2023)

Logs quality	Diameter classes (cm)	Length (m)
A1	30 up	1.00
A2	30 up	1.30
A3	25–29	1.00
A4	25–29	1.30
A5	20–24	1.00
A6	20–24	1.30
A7	18–19	1.00
A8	18–19	1.30
B1	30 up	1.00 or 1.30
B2	20–29	1.00 or 1.30
B3	16–19	1.00 or 1.30
B4	12–15	1.00 or 1.30
B5	10–11	1.00 or 1.30

2.4. Development of Predicting Models

A total of 31 trees were sampled and utilized in developing the residual volume model. The estimating models employed in this study encompassed both linear and nonlinear regressions. In this case, the dependent variable is the volume of the harvesting residues (*Vfr*), while the independent variable, or predictor, is the total volume of the felled trees (*VolTot*). The linear and nonlinear regression analyses were performed using R software version 4.3.0, employing ordinary least squares techniques (Atanlogun et al. 2014; Team 2023). The model utilized in this study incorporated a modification of the prevalent regression models commonly employed in the forestry literature (Husch et al. 2009; Santos et al. 2019) as shown in Equation 1–4.

$$Vfr1:\ V = b_o VolTot^{b1} \quad (1)$$

$$Vfr2:\ V = b_o + b_1\ VolTot^2 \quad (2)$$

$$Vfr3:\ V = b_o + b_1\ VolTot + b_2\ VolTot^2 \quad (3)$$

$$Vfr4:\ V = b_o + b_1\ VolTot \quad (4)$$

The evaluation of regression models was conducted by employing goodness-of-fit statistics (Bennett et al. 2013; Sileshi 2014), namely the Root Mean Squared Error (RMSE) and the adjusted coefficient of determination (R^2adj).

3. Results and Discussion

3.1. Results

The diameters at breast height of the standing trees varied from 10.19 cm to 37.90 cm, with an average of 23.42 cm. The tree heights observed from the felling sampled trees ranged from 11.5 to 27.0 m, with an average height of 19.95 m. The commercial height varied from 2 to 15 m, averaging 9.22 m. This study found that around 46% of the overall height of the standing trees consisted of clear bole. The average diameter and length of logs resulting from felling operations varied greatly between log types. The stumps had the highest diameter (33 cm), whereas the branches had the lowest diameter (6 cm). Meanwhile, for log length, the branches were recorded as the type of log that has the highest length (2.59 m), while the butt ends have the lowest length (0.14 m). The diameter and length of the stumps were remarkably varied. It is due to the stump of some felled trees being attacked by tumor rust disease. This disease causes hyperplasia (more growth) on the stumps (**Table 3**).

Table 3. Diameter and length of various types of logs resulting from harvesting operation in private forest managed with agroforestry system in Probolinggo

Type of logs	**Diameter (cm)**			**Length (m)**		
	Min	**Max**	**Average**	**Min**	**Max**	**Average**
Usable logs	8	38	20	1.30	1.30	1.30
Stumps	16	59	33	0.08	0.60	0.16
Butt ends	9	29	19	0.18	0.20	0.14
Top logs	9	20	18	0.10	1.30	0.42
Branches	4	13	6	1.40	6.00	2.59

Notes: Min = minimum and Max = maximum.

The total volume of logs obtained from 31 selected trees was approximately 20.61 m³, with an average volume of 0.66 m³/tree. The largest volume proportion of logs consists of the usable logs (89.03%), followed by the top logs (5.48%), stumps (2.57%), branches (1.65%), and butt end (1.26%) (**Table 4**). The wood processing industry utilized a usable log volume of 19.39 m³, while the volume of harvesting residues was 1.22 m³ (**Table 4**). The residue factor of the harvesting operation in the study site was approximately 0.06, while the utilization factor was 0.94. This study demonstrated that the usable logs of private forests managed with an agroforestry system in Probolinggo were high. Most usable logs were derived from the commercial stem (94.64%), with a smaller proportion originating from the upper stem (5.36%). The volume of stumps comprised 43.44% of the total volume of harvesting residues. Subsequently, the remaining volume was distributed among butt ends, top logs, and branches.

Table 4. Total volume, utilization volume, and residue volume of harvesting operation in a private forest managed with agroforestry system in Probolinggo

Type of logs	**Total Volume**		**Utilization volume**		**Residue volume**	
	(m³)	**(%)**	**(m³)**	**(%)**	**(m³)**	**(%)**
Usable logs	18.35	89.03	18.35	94.64	0,00	0.00
Stumps	0.53	2.57	0.00	0.00	0.53	43.44
Butt ends	0.26	1.26	0.00	0.00	0,26	21.31
Top logs	1.13	5.48	1.04	5.36	0,09	7.48
Branches	0.34	1.65	0.00	0.00	0,34	27.89
Total	20.61	100.00	19.39	100.00	1.22	100.00

Based on the classification of diameter classes, most harvesting residues were predominantly in the diameter class greater than 10 cm (75.44%). This result is followed by the diameter class of 8–9 cm, which accounts for 14.14% of the volume of harvesting residues. The diameter class of 6–7 cm contributes 6.58%, while the 4–5 cm diameter class represents 2.32%. In addition, the 9–10 cm diameter class contributed to 1.25% (**Table 5**).

Table 5. Diameter classes and volume of harvesting residues in a private forest managed with an agroforestry system in Probolinggo

Diameter classes (cm)	Volume of various types of logs (m^3)				Total	
	Top logs	Butt ends	Branches	Stumps	(m^3)	(%)
4–5	0.00	0.00	0.03	0.00	0.03	2.32
6–7	0.00	0.00	0.07	0.00	0.07	6.58
8–9	0.00	0.00	0.16	0.00	0.16	14.41
9–10	0.09	0.02	0.00	0.00	0.11	1.25
> 10	0.00	0.24	0.08	0.53	0.85	75.44
Total	0.09	0.26	0.34	0.53	1.22	100.00

The study revealed that all models utilized for calculating the volume of harvesting residues had a similar RMSE of approximately 0.03 (**Table 6**). Nevertheless, the models *Vfr2*, *Vfr3*, and *Vfr4* show specific parameters (b_0, b_1, dan b_2) that lack significance, as indicated by their p-values exceeding 0.01. As a result, we opted against selecting these models to predict the volume of harvesting residue. The model selected for estimating the residual volume is *Vfr1*, demonstrating reliability. The predictor variable utilized in this model is the total volume of felled trees.

Table 6. The goodness of fit from the models of the volume of harvesting residue using the total volume of felled trees as a predictor

Models	Parameters	SE	P-value	RMSE	R^2adj	Models
Vfr1	b_0	0.042	0.169	0.000	0.030	0.630
	b_1	1.248	0.169	0.000		
Vfr2	b_0	0.011	0.008	0.157	0.020	0.380
	b_1	0.038	0.008	0.000		
Vfr3	b_0	0.009	0.017	0.610	0.020	0.360
	b_1	0.007	0.053	0.892		
	b_2	0.033	0.034	0.332		
Vfr4	b_0	-0.004	0.011	0.683	0.020	0.360
	b_1	0.057	0.013	0.000		

Notes: SE = standard error, RMSE = root mean squared error, and R^2adj = adjusted coefficient of determination.

3.2. Discussion

The utilization factor of harvesting operation in private forest managed with an agroforestry system for sengon in Probolinggo was 94% of the total volume of the harvested trees. The previous study related to this factor on a teak private forest had a smaller value. According to Budiaman and Komalasari (2012), the volume of usable logs in a teak forest in Konawe Selatan was 77.7%. When comparing the findings of this study with those of previous studies conducted in large-scale plantation forests, it is evident that this study demonstrates a higher value for the utilization factor. The percentage of usable logs in plantation forests for mangium was 76.70% (Budiaman and Kartika 2004), while for teak, it ranged from 79.61% to 86.00% (Budiaman et al. 2014; Matangaran and Anggoro 2012). This tendency explains that harvesting a sengon private forest managed with an agroforestry system has a high utilization factor despite the relatively young age of the felled trees (5 years old). This outcome may arise due to the utilization of agroforestry woods in the wood processing industry, as it does not require high-quality wood. Sengon, from a private forest managed with an agroforestry system in Probolinggo, has been utilized as a primary material for producing laminated veneer lumber (LVL) and plywood. Furthermore, the present study has revealed that the volume of the usable logs varies depending on the specific site and timber species. A previous study in Finland found that the utilization factor contributed from 65% to 70% (Kallio and Leinen 2005).

The study showed that stumps contain the most frequent residual wood, followed by branches, butt ends, and top logs. The study found a different result than previous research. In teak private forests, branches were the most frequent residual wood, accounting for 46.15% of harvesting residue volume, while stumps accounted for only 7.69% (Budiaman and Komalasari 2012). In teak plantation forests, branches also comprised the majority of harvesting residues, followed by stumps and butt ends (Budiaman et al. 2016; Matangaran et al. 2013). The harvesting operation conducted in a private forest managed with an agroforestry system in Probolinggo results in a higher number of stumps compared to other locations. There could be reasons for this issue. Firstly, it is possible that the felling notch was not made parallel to the ground surface. Secondly, the presence of a defect in the stumps may also contribute to the problem. The average stump height susceptible to disease ranges from 16 to 60 cm. Stump portions as harvesting residues can be reduced by lowering the notch cut as much as possible and pressing the stump if the defects do not diminish the wood's quality. According to Kallio and Leinen (2005), the amount of usable logs increased when stumps were extracted from the forest.

Even though the stump showed a diameter exceeding 10 cm, its length measured less than 1 m. The local people used the harvesting residues of sengon at the study site as firewood. Small-diameter wood is better suited for use in the bioenergy, pulp and paper, and wood pellet industries than sawn timber or veneer. Some developed countries, such as Finland, the United Kingdom, Australia, and the United States, as well as some Asian and African nations, use short and small logs from harvesting residues as a source of bioenergy (Adamczyk et al. 2014; Giuntoli et al. 2015; Osman et al. 2014; Zamora-Cristales and Sessions 2016). In addition, forest residue can be used to produce various products, including compost and animal bedding (Pandey 2022).

The factor residue of harvesting operation in the study site was low, amounting to only 0.06. When the harvesting residue is extracted from a forest, only small branches (4 cm) remain in the forest. The extraction of harvesting residues outside the forest will influence the overall functioning and dynamics of the forest ecosystem (Giuntoli et al. 2015; Numazawa et al. 2017; Ojanen et al. 2017). In contrast, leaving significant amounts of harvesting residues in the forest can lead to environmental issues such as carbon emissions and soil quality (Victor et al. 2014). Norway's spruce (*Picea abies*) forest harvesting leaves behind approximately 40% of residual wood. At least one-third of this quantity is harvesting residue at the logging site (Peltola et al. 2011). According to Mills et al. (2023), it has been observed that tropical forests that have undergone harvesting activities contribute to the release of carbon into the atmosphere. The present source originates from logging residues left in the forest with a minimum longevity of 10 years after the harvesting activity. According to the findings of Ranius et al. (2018), the removal of forest residues can exert a substantial impact on the biodiversity of forest ecosystems.

The study indicated that most harvesting residue had a diameter class greater than 10 cm, accounting for 75.44% of the total residue volume. The remaining portion of the harvesting residue had a diameter class of less than 10 cm. This information indicates that the harvesting residue from private forests managed with an agroforestry system consists of small-diameter logs. The result of this study is in line with the previous study. Filko et al. (2013) reported that the diameter distribution of harvesting residues often seen in Brazil ranges from 10–20 cm.

The study indicated no difference in the RMSE values among all the models used to estimate the volume of harvesting residues, as they all had an RMSE value of 0.03. Additionally, the independent variable, the total volume of felled trees, accounted for 36–63% of the variability observed in the volume of harvesting residue (**Table 6**). Nevertheless, the *Vfr2*, *Vfr3*, and *Vfr4* models had non-significant parameters (b_0, b_1, and b_2) with P-values greater than 0.01. Consequently, these models were deemed unsuitable for accurately predicting the volume of harvesting residues. Hence, *Vfr1* can be considered a dependable model for estimating the volume of harvesting residues by utilizing the variable of the total volume of felled trees. The equation model presented in this study aligns with existing tree volume estimate models that employ diameter as the independent variable, which has been identified as the most effective model in the previous study (Susanty and Abdurrachman 2016; Tiryana et al. 2021).

The study demonstrated that the *Vfr1* model can estimate the volume of harvesting residues at the study site. Total tree volume as an independent variable can explain the volume of harvesting residues by 63%, and other factors influence the rest. This model is simple and applicable enough to help determine the efficiency level of harvesting agroforestry private forests without measuring felling residues.

4. Conclusions

The study has gathered substantial data about the residual wood derived from the harvesting operations conducted in private forests managed with agroforestry systems with sengon as the harvested timber species. The study showed that only a few harvesting residues were left in the private forests after harvesting operations. Detailed measurements in the study site showed a residue factor of approximately 0.06. The majority of harvesting residues consisted of stumps. The study found that the standing tree volume can be used to estimate the volume of harvesting residue in the private forests managed with the agroforestry system in Probolinggo.

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