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Determination of Harvesting Cycle of *Gliricidia sepium* for Bioenergy Using Growth Model

Penentuan Siklus Pemanenan Gliricidia sepium *untuk Kayu Energi Menggunakan Model Pertumbuhan*

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RESEARCH ARTICLE

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ABSTRACT

The emission of CO_2 is increasing due to the high population and standard of living, particularly from the energy sector. Renewable energy from forest resources, such as fuelwood, can contribute to these emissions' reduction. Therefore, this research aimed to generate a growth model to determine the harvesting cycle of *Gliricidia sepium* as a source of raw material for bioenergy. The model generation employed regression technique and used stand inventory data. The growth model for *Gliricidia sepium* was $Y = 157.46e^{(-3.342/A)}$, where age (A) was the independent variable. The optimum harvest occurred at 4 years with a biomass production potential of 68.28 tons/ha. This research provided valuable information for decision-making in managing the industrial forest plantation of *Gliricidia sepium* for bioenergy.

INTISARI

Peningkatan jumlah penduduk dan taraf hidup menyebabkan meningkatnya emisi CO_2*, terutama dari sektor energi. Salah satu cara untuk mereduksi emisi ialah dengan menggunakan energi baru terbarukan dari sumber daya hutan, seperti kayu bakar. Penelitian ini bertujuan untuk menyusun model pertumbuhan untuk menentukan siklus pemanenan* Gliricidia sepium *sebagai kayu energi. Teknik regresi digunakan dalam menyusun model estimasi biomassa dan pertumbuhan berdasarkan data inventarisasi tegakan. Penelitian ini menghasilkan model pertumbuhan* Gliricidia sepium *dengan persamaan* $Y = 157.46e^{(-3.342/A)}$*, di mana umur (A) menjadi variabel penduga. Panen optimal tercapai pada usia empat tahun dengan potensi produksi biomassa 68,28 ton/ha. Penelitian ini memberikan informasi penting untuk pengambilan keputusan dalam pengelolaan hutan tanaman energi* Gliricidia sepium.

Introduction

The emission of CO_2 is increasing due to the high population and standard of living. Future energy demand tends to increase due to climate change, but the magnitude depends on several interacting sources of uncertainty. Vigorous (moderate) warming increases global climate-exposed energy demand before adaptation around 2050 by 25–58%, in addition to a factor 1.7–2.8 increase above present-day due to socioeconomic developments (van Ruijven et al. 2019). In response, the Indonesian Government is committed to reducing CO_2 emissions by ratifying the Paris Agreement by enacting Law No. 16 of 2016 and formulating the Nationally Determined Contribution (NDC). This effort targets a reduction in greenhouse gas emissions by 31.89% unconditionally and 43.20% with international support. An effective strategy to reduce CO_2 emissions in the energy sector is to increase the use of renewable energy. The government has set targets in Government Regulation No. 79 of 2014 on National Energy Policy, aiming for a 23% and 31% renewable energy mix by 2025 and 2050, respectively. This energy mix will also include the implementation of co-firing in PLN (State Electricity Company) coal-fired power plants and other industries.

The forestry sector is responsible for providing raw materials to support the increase in renewable energy. Since 1961, Indonesia has produced fuelwood in the form of charcoal, which later evolved into wood pellet production in 2012 and briquettes in 2017 (Food and Agriculture Organization 2023). However, most fuelwood raw materials are obtained from logging residues, forest land conversion, and smallholder plantations (Udali et al. 2024). There is a need for forest management that focuses on producing fuelwood raw materials. Wood, as a renewable energy raw material, has the advantage of being emissions-neutral when balanced with replanting efforts in subsequent years (Sasaki 2021). The development of forest plantations is crucial to support the supply of fuelwood raw materials, with one promising crop being *Gliricidia* (*Gliricidia sepium*).

Gliricidia, a member of the Fabaceae family, thrives in tropical climates with annual rainfall of 900-1,500 mm (Elevitch & Francis 2006). This plant has potential as bioenergy, with a productivity of 10-20 m^3 per hectare on a 2–3 years harvest rotation and a calorific value of up to 4,900 kcal/kg. Previous research reported varying characteristics, including a diameter range of 0.1-22.5 cm for 1–5-year-old plants (Mulyana et al. 2020b), moisture content of 8.25% in powdered form, and 26.8% in chopped form (Junior & Mujiono 2023), and a gross calorific value of 19.55 MJ/kg (Oyelere & Oluwadare 2019). Additionally, the management of *Gliricidia* plantations can be technically developed using a coppicing system, especially short rotation coppice (SRC). The SRC method is designed to produce raw wood materials with low capital investment but high returns (Fabbio 2016; Nicolescu et al. 2017).

The limitation of fossil resources and efforts to reduce CO_2 emissions encourage efforts to switch to using new and renewable energy, one of which is wood. This new renewable energy needs to consider its demand for a sustainable supply of raw materials on an industrial scale. Analysis of stand productivity and growth is crucial in maintaining sustainable timber production, biodiversity, and other ecosystem functions. The development of growth models to assess the current stand stock, predict future yields, and provide alternative management models as a basis for decision-making in sustainable forest management (Bian et al. 2023). Growth models are used in decision-making to predict future yield and optimal rotation period for harvesting *Gliricidia* wood biomass. Previous research discussed little about growth models and harvest cycle optimization for *Gliricidia* plants as a raw material for renewable energy. This research aimed to develop a growth model for *Gliricidia* stand and optimize its harvest cycle based on the growth model of *Gliricidia* stands for bioenergy.

Methods

Time and Location

This research was conducted from October 2023 to July 2024 at Perum Perhutani. Sample plots were selected purposively to represent non-coppice stands planted in 2019, 2020, and 2021 and coppice stands harvested in 2021. The stand spacing was 2 m × 1 m, equivalent to 5000 trees per hectare. The selection also considered accessibility, time, and cost factors. The sample plots comprised 33 non-coppice and 12 coppice plots, totaling 45 sample plots. The non-coppice sample plots were distributed in West Java and Banten Regional Division (12 plots), Central Java (9 plots), and East Java (12 plots). Meanwhile, the coppice sample plots were distributed in KPH Semarang, Central Java Regional Division (10 plots), as summarized in Table 1.

Data Collection

This research used primary data collected from the inventory of *Gliricidia* stands and destructive samples obtained by harvesting the biomass of the *Gliricidia* stands (cutting tests). The inventory of *Gliricidia* stands used 20 m × 10 m sample plots and diameter measurement at breast height (dbh) for each stem in a tree for all trees in the sample plots. A stand representation of coppice and non-coppice was selected for cutting tests to obtain stem diameter and weight after felling. This research purposely selected a cluster within each representation stand by considering the distribution of the smallest to largest stem diameters. Within each cluster, 17 coppice and 17 non-coppice stems were randomly selected for biomass harvesting. The diameters of the stems were first measured before they were pruned at 30 cm above the ground level. The trimmed stems were cut into 1 m lengths and tied using raffia rope to facilitate weighing with a digital hanging scale (Figure 1).

This research used secondary data, including

Table 1. Distribution of sampling plots of *Gliricidia*

Regional Division	KPH	BKPH	RPH	Plot	Q	A	Description
West Java and Banten	Indramayu	Sanca	Sanca	43A	2	3	NC
West Java and Banten	Indramayu	Sanca	Sanca	41A	2	4	NC
West Java and Banten	Purwakarta	Cipeundeuy	Cijangkar	62G-3	2	3	NC
West Java and Banten	Sukabumi	Lengkong	Hanjuang barat	94J-1	4	3	NC
West Java and Banten	Sumedang	Conggeang	Sampora	8D-2	2	2	NC
Central Java	Purwodadi	Karangasem	Peting	16C-2	2	3	NC
Central Java	Purwodadi	Karangasem	Karangasem	9D	2	2	NC
Central Java	Semarang	Kedungjati	Pepe	17B	2	4	NC
Central Java	Semarang	Kedungjati	Kedungjati barat	8B	1	3	NC
Central Java	Telawa	Gemolong	Juranggandul	8D	2	4	NC
East Java	Bojonegoro	Tretes	Tretes	12B-2	2	3	NC
East Java	Bojonegoro	Tondomulo	Malangbong	41A	2	2	NC
East Java	Padangan	Kaliaren timur	Kedungpoh	11D-2	3	4	NC
East Java	Padangan	Ngraho	Meduri	120B-1	2	4	NC
East Java	Saradan	Pajaran	Pajaran	165B	3	2	NC
Central Java	Semarang	Tanggung	Mliwang	199A-1	3	2	C
Central Java	Semarang	Tanggung	Sugihmanik	197A	2	2	C
Central Java	Semarang	Tanggung	Mliwang	184E	2	2	C
Central Java	Semarang	Tanggung	Mliwang	193A	2	2	C
Central Java	Semarang	Padas	Salam	208A	1	2	C

Notes: Q = quantity of plots; A = aged (years); NC = non-coppice; C = coppice

Figure 1. *Gliricidia* weight measurement activities of (a) coppice stem and (b) non-coppice stem after stem measurement, pruning, and cutting

information on *Gliricidia* forest management, such as the location of the plant areal distribution, cutting test data from the 2022 harvesting activities, operational costs of forest management, and the selling value of *Gliricidia* wood obtained through interviews.

Biomass Estimation Model

Mulyana et al. (2020b) developed a biomass estimation model for *Gliricidia* to estimate tree biomass using 30 cm above-ground diameters. This research considered the characteristics of *Gliricidia* plants, namely the type of plant with more than one branch (multi-stem) and the silviculture system applied in the form of coppice system regeneration. The biomass stock estimation used the diameter of the breast height (dbh) and the weight of tree biomass in coppice and non-coppice stands as independent variables. This research modified the three best models from Mulyana et al. (2020b), as summarized in Table 2.

Along with the allometric model of *Gliricidia* biomass construction, this research performed the classical assumptions tests, including normality, heteroscedasticity, and lack of fit tests, to ensure accurate, reliable, unbiased, or inconsistent estimation. The Kolmogorov-Smirnov normality test aimed to test whether the residual data was normally distributed. When the p-value was less than the significance level (α), the null hypothesis (Ho) was rejected, suggesting that the residual data was not normally distributed. Conversely, when the p-value was greater than or equal to the significance level (α), the null hypothesis (Ho) was accepted, suggesting that the residual data was normally distributed. The Glejser heteroscedasticity test aimed to check whether the model had uniform variance. When the p-value was less than the significance level (α), the null hypothesis (Ho) was rejected, suggesting that there was an indication of heteroscedasticity in the model. When the p-value was greater than or equal to the significance level (α), the null hypothesis (Ho) was accepted, suggesting no indication of heteroscedasticity. The Gauss-Newton lack of fit test or model fit aimed to ensure that the regression model could explain the variation in data. When the p-value is less than the significance level (α), the null hypothesis (Ho) was rejected, suggesting that the relationship assumed in the model was not reasonable (there is a lack of fit). Conversely, if the p-value is greater than or equal to the significance level (α), the null hypothesis (Ho) was accepted, suggesting the relationship assumed in the model was reasonable (there is no lack of fit).

The best biomass model of *Gliricidia* was determined by the t-test, error by root mean square error (RMSE), and mean absolute error (MAE). The t-test used Minitab version 22 to test the significance of the difference between the predicted values generated by the model and the actual observed values. Decision-making is based on the comparison between the significance level (α). When the p-value is less than the significance level, the null hypothesis (Ho) was rejected, indicating a statistically significant difference in the means between the actual observed values and prediction values. Conversely, if the p-value was greater than or equal to the significance level, the null hypothesis (Ho) was accepted, suggesting no significant difference in the means between actual observed values and prediction values (Gravetter & Wallnau 2016). RMSE and MAE values were obtained by using the following equations.

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(Y-Y')^2}{n}}$$

$$\text{MAE} = \frac{\sum_{i=1}^{n}[Y-Y']}{n}$$

Y' represented the model's predicted value, Y represented the actual observed value, and n was the

Table 2. The modified biomass estimation model of *Gliricidia* by Mulyana et al. (2020b)

Model	Equations
Power	$B_n = \beta_o \times D^{\beta_1}$
Exponential	$B_n = \beta_o \times e^{(\beta_1 D)}$
Polynomial	$B_n = \beta_o + \beta_1 D + \beta_2 D^2$

Notes: B_n = biomass of stem; D = dbh of stem (130 cm); β_n = regression coefficient number of data points. Lower error values (RMSE and MAE) indicated a model's improved ability to predict or represent the data accurately. The optimal biomass model was determined by a scoring method considering the highest p-value obtained from the t-test, the RMSE, and the MAE metrics.

Growth Model

The selected model was applied to estimate the biomass stand stock and develop a growth model. Due to its environmental impact, forest management became a subject of interest across multiple disciplines, including forestry, economics, and ecology. Research from these fields developed models designed for specific areas. Economists focused on determining the optimal age for harvesting individual trees or entire forest stands and managing multiple stands simultaneously. Meanwhile, foresters were primarily concerned with silvicultural practices at the stand level (Bian et al. 2023). The growth models used in this research were based on the work of Bruce & Schumacher (1950), Prodan (1968), and Vanclay (1994), as summarized in Table 3. The normality, heteroscedasticity, and lack of fit tests were conducted using Minitab version 22.

Determination of Harvesting Cycle

The observation of the *Gliricidia* harvesting period was conducted based on the intersection between the mean annual increment (MAI) and current annual increment (CAI), also known as the biological cycle (Siarudin & Indrajaya 2017). The calculation model for MAI and CAI followed the equation proposed by Prodan (1968).

$$\text{MAI} = \frac{Volume}{Aged}$$

$$\text{CAI} = \frac{V_{(n+1)} - V_n}{T_{(n+1)} - T_n}$$

Where V_n represented the stand volume at age n (m^3/ha), and T_n represented the stand age (years). The units of MAI and CAI are m^3 per hectare per year.

Result and Discussion

The biomass production estimation and optimum harvesting cycle determination of the *Gliricidia* stand were carried out by analyzing the relationship between the biomass growth parameters and stand age. This process included collecting cross-sectional field data by considering the representativeness of stand age, applying biomass allometric, and using growth models. The peak point of the growth function determined maximum production, while the optimum harvest occurred at the age where MAI and CAI intersected.

Biomass Estimation

The *Gliricidia* biomass estimation used allometric models generated from 2022 and 2023 cutting test data of coppice and non-coppice stands (Figure 2). The *Gliricidia* biomass estimation used allometric models generated from 2023 cutting test data of coppice and non-coppice stands (Figure 2). The graphs showed the relationship between the stem diameter (cm) and the biomass (kg) power, exponential, and polynomial models. All generated biomass allometric models showed consistent results with slight differences. However, the exponential model had a higher estimation than others at 8 cm diameter and greater. Classical assumption tests were carried out to assess the generated models, as summarized in Table 4. The Glejser test indicated the presence of heteroscedasticity in the polynomial allometric model (p-value < 0.05). For this reason, the polynomial model was eliminated to estimate *Gliricidia* biomass.

Furthermore, the comparison of RMSE and MAE of power and exponential allometric models indicated that the power model had the highest p-value,

Table 3. The growth models to estimate the stand growth of *Gliricidia*

Model	Equations
Bruce and Schumacher	$Y = \beta_o \times e^{(-\beta_1/A)}$
Prodan	$Y = A^2 / (\beta_o + \beta_1 A + \beta_2 A^2)$
Vanclay	$Y = e^{(\beta_0 + \beta_1 A)}$

Notes: Y = biomass production (ton/ha); A = age (years); β_n = regression coefficient; e = exponential function

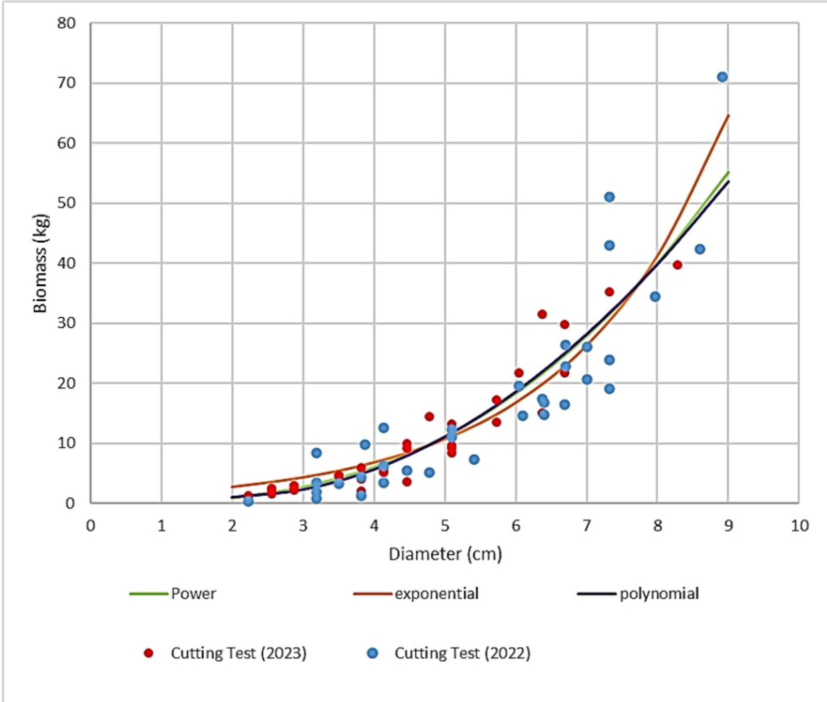

Figure 2. Distribution of cutting test data in 2022 and 2023 against the power, exponential, and polynomial model curves

Table 4. Classical assumptions test of the *Gliricidia* biomass allometric models

Model	p-value		
	Normality	Heteroscedasticity	Lack of Fit
Power : $Bn = 0.14Dn^{2.718}$	0.15	0.68	0.80
Exponential : $Bn = 1.14e^{0.45Dn}$	0.17	0.31	0.23
Polinomial : $Bn = 4.796 - 3.932Dn + 1.039Dn^2$	0.14	0.00*	0.83

Notes: Bn = stem biomass; Dn = stem diameter; *significant level (α) 0.05

Table 5. Comparison of RMSE and MAE of the *Gliricidia* biomass allometric models

Model	p-value		
	RMSE	MAE	T-test
Power : $Bn = 0.14Dn^{2.718}$	6.67(1)	0.99(2)	0.40(2)
Exponential : $Bn = 1.14e^{0.45Dn}$	6.28(2)	1.16(1)	0.29(1)

Notes: Bn = stem biomass; Dn = stem diameter; RMSE = Root Mean Square Error; MAE = Mean Absolute Error; (1),(2) = rank of scores

showing a realistic tendency to biomass estimation from the field data of *Gliricidia* stands (Table 5). Therefore, the power allometric model was selected to estimate the biomass stock of *Gliricidia* stands.

Subsequently, the power allometric model was employed to estimate the biomass production of *Gliricidia* stands that considered multi-stem tree characteristics by transforming the allometric model as follows.

$$B_n = \sum_{i=0}^{n} (0{,}14Dn^{2{,}718})$$

B_n represented stem biomass and D_n represented stem diameter.

The diameter size and the biomass stocks positively correlated with the stand age. In contrast, the number of stems and stand density negatively correlated with the stand age (Figure 3). The competition for nutrients and sunlight led to the natural thinning of *Gliricidia* stands (Barbosa et al. 2023). Coppice stand regenerates through shoots or root suckers arising from the stumps of previously cut trees or shrubs. There were two main coppice woodland management systems, namely the simple and standard coppice. Simple rotation coppice (SRC) was a specific type primarily found on agricultural land. In SRC, the lifespan of the shoots was relatively short, lasting between 1 and 3 years, contrary to the traditional woodlands. The stools required replanting after 5-7 rotations, or about every 12-20 years, to maintain site productivity. However, the development of SRC faced multiple challenges. These included high moisture content in freshly cut chips, technical difficulties in rough terrain, increased costs for small-scale operations, dependency on harvester availability, and reduced biodiversity compared to traditional woodlands (Nicolescu et al. 2017; Unrau et al. 2018).

External and environmental factors, such as land fires, uncontrolled grazing, slope steepness, soil solum depth, and climate conditions, influenced biomass production at each age (Fabbio 2016). The comparison between 2-year stands indicated that the biomass of the coppice tree was significantly higher than that of the non-coppice tree (Figure 3) due to the developed and established root system from the period before harvesting (Unrau et al. 2018).

Growth Model

The growth model was developed using only non-coppice stand data due to the limited age variation in coppice stands. The analysis of 33 observation plots of non-coppice stands indicated that biomass

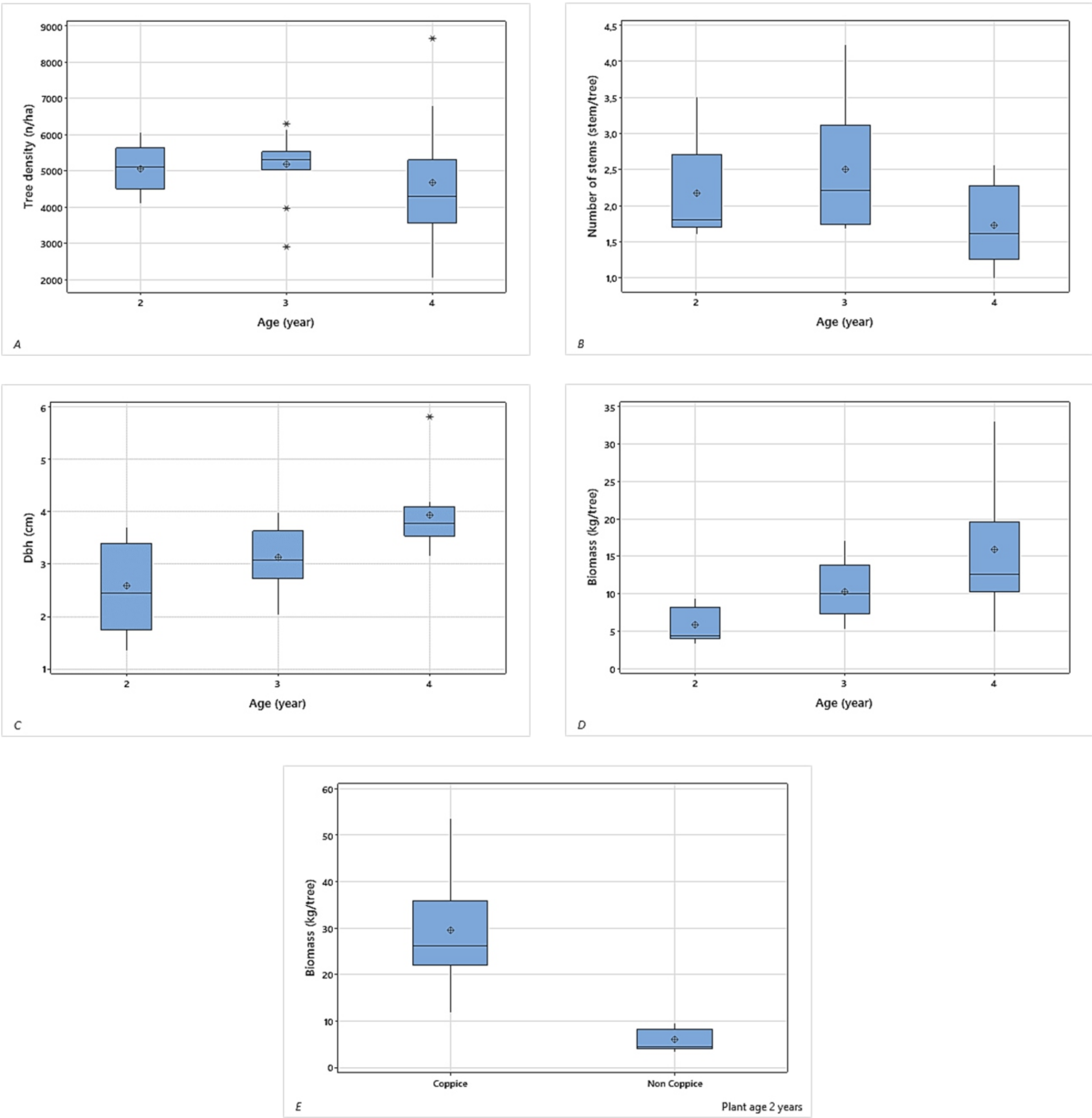

Figure 3. Distribution of the number of (A) tree density by age, (B) number of stems, (C) dbh, (D) biomass, and (E) comparison coppice and non-coppice of *Gliricidia* stands

production positively correlated with stand age, indicating progressed stand growth (Table 6). However, as the stand aged, the variation in biomass production also increased, particularly at age four, likely due to competition among trees. Additionally, at the age of four, there were stands with very low biomass production (17.24 tons/ha), suggesting the presence of abnormal growth in some stands. Low biomass production was observed in KPH Padangan, BKPH Ngraho, RPH Meduri, specifically in plot 120B-1. The low biomass production was attributed to forest encroachment by surrounding communities of the Forest Area with Special Management (KHDPK) to practice intercropping with seasonal crops such as corn (Figure 4), which disrupted the growth of *Gliricidia* trees. Consequently, this data point was eliminated from the analysis, resulting in 32 observation plots of non-coppice stands for the growth model development.

The Kolmogorov-Smirnov normality test showed that all models obtained a p-value greater than 0.05, indicating that the residuals were normally distributed. In the Glejser heteroscedasticity test, the models obtained a p-value greater than 0.05, indicating no significant difference between the predicted (Y') and the observed dependent variable (Y). The Gauss-Newton model fit test indicated that the Bruce-Schumacher and Vanclay models achieved a p-value greater than 0.05, suggesting that all equations were consistent with the data. However, the Prodan model had no lack-of-fit value, as the equations were inconsistent with the data (Mardiatmoko 2020). The Bruce and Schumacher model became the best growth model because it met all the classical assumption tests (Table 7). The model fitted with the distribution of potential biomass production of non-coppice *Gliricidia* stands by age and extrapolated up to five years (Figure 5).

Table 6. Descriptive statistic of 32 non-coppice stands observation plots

Variable	Age (year)	Mean	Standard Deviation	Minimum	Maximum
Biomass production (ton/ha)	2	30.40	15.10	16.53	57.00
	3	50.74	16.32	27.74	79.56
	4	68.84	28.94	17.24	117.25

Figure 4. Intercropping of *Gliricidia* with corn

Table 7. Classical assumptions test of the *Gliricidia* growth models

Model	p-value		
	Normality	Heteroscedasticity	Lack of Fit
Bruce and Schumacher : $Y = 157.46e^{(-3.342/A)}$	0.98(3)	0.56(2)	0.22(2)
Prodan : $Y = A^2/(0.019 - 0.063A + 0.003A^2)$	0.78(2)	-	0.23(3)
Vanclay : $Y = e^{(2.632 + 0.42A)}$	0.52(1)	0.66(3)	0.19(1)

Notes: Y = biomass production (ton/ha); A = age (year); e = exponential function; (1), (2), (3) = rank of scores

Harvesting Cycle

The growth of most living organisms followed a sigmoid (S-shaped) curve including trees. Furthermore, the growth of trees typically progresses through three main phases, namely an initial slow growth phase (youth), a rapid (maturity), and a final phase of slowing growth (senescence). Different research referred to these stages using various terms, such as acceleration, full vigor, and old age. In the first phase, growth followed an exponential pattern, gradually increasing until reaching an inflection point. The second phase showed a steady, linear growth rate, while the third experienced a gradual decline in growth (Salas-Eljatib et al. 2021). Suhartati & Pebriansyah (2021) suggested that the growth phase consisted of the initial and the maximum growth phases. The initial growth phase was shown by CAI being higher than MAI, where height, diameter, and volume increased rapidly. The maximum growth phase was shown by MAI being higher than CAI, where height, diameter, and volume peaked before experiencing a decline. Between the initial and maximum growth phase was the transitional growth, where the curve experienced a decline due to competition among individual trees for nutrients and sunlight, leading to mortality. Maximum growth, shown by the intersection between CAI and MAI, could determine the forest's optimal harvesting cycle (rotation period) for maximum productivity.

This research conducted observations on stand aged 2–4 years. The identified growth phases in the curve commenced with the linear at 2 years, followed by a decline in growth at 3 years, and transition into the asymptotic phase. The initial growth phase occurred at 0–4 years old, where CAI was higher than MAI. CAI showed a significant increase, reaching its peak at 2 years old with a biomass production potential of 24.04 tons/ha. *Gliricidia*'s productivity peaked at 3 years old, averaging 17.23 tons/ha/year. The intersection of the CAI and MAI curves occurred at 4 years old, indicating the optimum harvesting cycle with biomass productivity at 17.07 tons/ha/year and biomass production at 68.28 tons/ha (Figure 6). While *Gliricidia*'s productivity was lower than *Calliandra*'s,

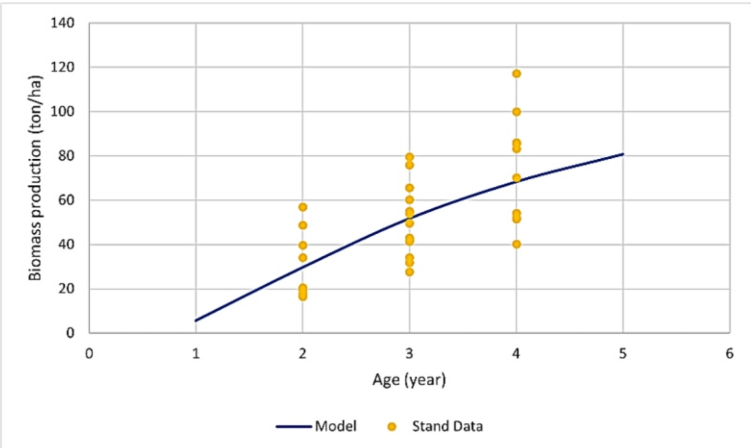

Figure 5. Distribution of potential biomass production of non-coppice *Gliricidia* stands by age and the Bruce and Schumacher growth curve

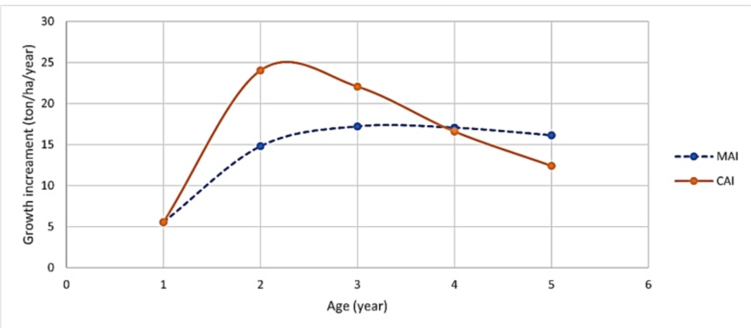

Figure 6. Biomass growth increment of *Gliricidia* stands

the species offered bioenergy raw material production potential, especially with optimized management (Febijanto 2020; Mulyana et al. 2020a).

Conclusion

In conclusion, multi-stem characteristics and the short rotation coppice (SRC) silvicultural system influenced the estimation of *Gliricidia* biomass. The SRC allowed for maintenance through repeated harvesting every 3-5 times, followed by final dismantling and replanting to maintain the productivity and quality of wood biomass. The SRC and non-coppice systems significantly differed in the number of branches. The *Gliricidia* stands with the SRC system grew numerous new shoots after being harvested. In this research, the power allometric model based on diameter as the primary predictor provided the best estimate for *Gliricidia* biomass. The Bruce and Schumacher growth model fitted the best observation data, with *Gliricidia* stand age (A) as the predictor variable. The optimum harvesting cycle of the non-coppice *Gliricidia* stands was 4 years, with a biomass production of 68.28 tons/ha. Unfortunately, the distribution of coppice *Gliricidia* stands lacked sufficient age variation, limiting the development of a growth model for coppice regeneration.

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